Universidad Nacional Mayor de San Marcos

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Facultad de Ingeniería Electrónica y Eléctrica

Escuela Profesional de Ingeniería Electrónica

Diseño e implementación de un prototipo medidor de campos electromagnéticos de baja frecuencia

TESIS

Para optar el Título Profesional de Ingeniero Electrónico

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FACULTAD DE INGENIERÍA ELECTRÓNICA Y ELÉCTRICA

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Los suscritos Miembros de Jurado, nombrados por la Dirección de la Escuela Profesional de Ingeniería Electrónica de acuerdo a la Resolución Rectoral N° 03823-R-17, reunidos en la fecha bajo la Presidencia del Dr. Guillermo Tejada Muñoz e integrado por los Ingenieros: Ing. Alfredo Medina Calderón, Ing. Teófilo Matías Huablocho Pérez y el Dr. Víctor Manuel Cruz Ornetta (Miembro - Asesor)

Después de escuchar la Sustentación de Tesis del Bachiller **GÓMEZ RAMOS, Cristhiams (12190151),** para optar el Título Profesional de Ingeniero Electrónico por la modalidad de Titulación Ordinaria, quien expuso su **TESIS: "DISEÑO E IMPLEMENTACIÓN DE UN PROTOTIPO MEDIDOR DE CAMPOS ELECTROMAGNÉTICOS DE BAJA FRECUENCIA".**

Se acordó........APROBAR........por........UNANIMIDAD........

Con la Nota de........QUINCE........(15)

Ciudad Universitaria, 16 de mayo del 2019

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DECANO

Dedicatoria

Agradezco a Dios por haberme otorgado una familia maravillosa, luchadora, humilde, quienes han creído en mí siempre, dándome ejemplo de superación, humildad y sacrificio; enseñándome a valorar todo lo que tengo.

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Resumen

Los campos oscilantes electromagnéticos que ocurren naturalmente en el rango del espectro de muy baja frecuencia (VLF), es decir, de 1 a 32 kHz, son débiles y difíciles de detectar en condiciones normales. Estos eventos electromagnéticos VLF naturales se observan durante las tormentas eléctricas, en ciertos vientos de montaña y durante los terremotos. Por otro lado, los campos electromagnéticos VLF artificiales son más fuertes y se sospecha que causan efectos negativos en la salud. Las fuentes típicas de estas emisiones de frecuencias muy bajas incluyen televisores, ciertos dispositivos médicos, algunas estaciones de radio, instalaciones eléctricas domiciliarias y torres de líneas de transmisión de energía eléctrica.

Este proyecto consta en diseñar e implementar un equipo medidor de campos electromagnéticos de baja frecuencia de bajo costo para realizar el monitoreo de radiaciones no ionizantes, mediante el diseño e implementación de sensor isotrópicos de campo eléctrico y campo magnético, así como una unidad de procesamiento controlada por el microcontrolador PIC que realiza el procesamiento de datos en tiempo real, almacenamiento y presentación de los resultados de la medición.

Para el desarrollo de este prototipo se tendrá como referencia el analizador de campos electromagnéticos de baja frecuencia NARDA EFA 300, lo que se quiere lograr es realizar un equipo que tenga la misma funcionalidad que el equipo mencionado. El prototipo completo está conformado por tres componentes principales: Sonda de Campo Eléctrico, sonda de Campo Magnético, un equipo procesador de datos. El equipo se podrá hacer uso para realizar mediciones de campos electromagnéticos de baja frecuencia.

Palabras claves: Radiaciones no ionizantes, campos electromagnéticos, medidor de campos electromagnéticos, muy baja frecuencia, efectos biológicos.

Abstract

Electromagnetic fields that occur naturally are weak and difficult to detect under normal conditions. These electromagnetic fields are located in earthquakes and mountain winds.
In contrast, artificial electromagnetic fields are stronger and possibly cause health effects. (A. Hanna, Yuichi Motai, J.Vargue, & Titcomb, 2009)
The objective of this project is the design and implementation of a low-cost low frequency electromagnetic field meter for the monitoring of non-ionizing radiation, through the design and implementation of isotropic electric field and magnetic field sensors, as well as a processing unit controlled by the PIC microcontroller that performs real-time data processing, storage and presentation of the measurement results.
For the development of this prototype, the NARDA EFA 300 low frequency electromagnetic field analyzer will be taken as reference, what we want to achieve is to make a team that has the same functions as the mentioned equipment. The complete prototype consists of the main components: Electric Field Probe, Magnetic Field probe, data processing equipment. Low frequency electromagnetic equipment.
Keywords: Non-ionizing radiation, electromagnetic field, electromagnetic field meter, very low frequency, biological effects.

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Capítulo 1

Introducción

Planteamiento del problema

Las redes de energía eléctrica han tenido un crecimiento continuo en el Perú y el mundo. En el sector eléctrico, según el análisis de la prospectiva nacional e internacional, se espera una continua actividad en la producción de electricidad (Ornetta, 2012).

Para el año 2025, se espera un crecimiento en la demanda de electricidad a partir de proyectos mineros e industriales. Por lo tanto, la demanda de potencia estará entre 9500 MW y 12300 MW, debido a estos proyectos para el periodo de 2016-2018 la inversión privada ascenderá a 3985 millones de dólares (Osinergmin, 2017).

Estos proyectos abarcarán creaciones de centrales de generación eléctrica, las dos plantas de Centrales Térmicas de 500 MW en Ilo, La Central Hidroeléctrica Veracruz con un potencia de 635 MW, Central Hidroeléctrica Chavín II generando 600 MW, entre otras se instalará Líneas de Transmisión en la Sierra y Selva como también los proyectos de distribución en la Zona Sur (Osinergmin, 2017, p.294).

Todo esto implica ciertos impactos debido a la exposición de los campos electromagnéticos. Estas han causado diversas preocupaciones en el Perú y el mundo, por los posibles efectos sobre la salud de las personas (Campoy, 2016).

Como ejemplo se tiene las Líneas de Transmisión que se vienen instalando en el sector urbano de la ciudad de Lima, la cual se observa que por debajo y los lados laterales de las líneas de transmisión se encuentran personas habitando durante muchos años, y esto se debe al desconocimiento de normativas fijadas por el Ministerio de Energía y Minas que indican ciertas restricciones por ende las poblaciones vienen invadiendo espacios no permitidos en la ciudad.

Para Radiaciones No Ionizantes se establecen los “Valores Máximos de Exposición a Campos Eléctricos y Magnéticos a 60 Hz”, adoptando las Recomendaciones ICNIRP (International Commission on Non-Ionizing Radiation Protection

Además sirven de base para los estándares de Alemania, Australia, Nueva Zelanda, Japón, a la Unión Europea, y otros países. En el siguiente cuadro se presentan los Valores Máximos de Exposición a Campos Eléctricos y Magnéticos para líneas eléctricas de 60 Hz (Ministerio de energía y minas, 2012).

Tabla 1 Tipos de exposición

Tipo de exposición	**Intensidad de campo eléctrico (kV/m)**	**Intensidad de campo magnético (µT)**
Poblacional	4,2	83,3
Ocupacional	8,3	416,7

Cabe mencionar que en la actualidad se viene desarrollando el transporte urbano por el medio de tren eléctrico, donde también se observa líneas de transmisión que se encuentran a una distancia cercana a las cabezas de las personas; es por ello que también se realizaron mediciones de radiaciones no ionizantes por el Instituto Nacional de Investigación y Capacitación de Telecomunicaciones en conjunto con el Ministerio de Energías y Minas.

Así como se viene desarrollando el sector eléctrico en todos sus aspectos, el sector de salud viene implementándose, equipándose y reestructurando sus ambientes, para ello cada área usuaria de las distintas especialidades que existen en un hospital, clínicas están creciendo en equipos médicos y a la vez se tiene un aumento en la exposición de campos electromagnéticos en cada ambiente donde se usa a diario equipos biomédico. Otras de las aplicaciones que se tiene en esa banda de frecuencia de 1 Hz – 32 k Hz son los electrodomésticos, equipos informáticos, maquinaria industrial y equipamiento biomédicos, etc.

En el Perú se requiere nuevos hospitales y líneas de energía eléctrica que aporten al desarrollo del país, debido que el suministro de electricidad es un servicio público importante para iniciar procesos industriales y suministrar el consumo de los usuarios residenciales. De esta forma, la electricidad es una fuente que impulsa la actividad económica, comercio internacional y genera bienestar en los ciudadanos en su calidad de vida (Osinergmin, 2017).

Por ello es valioso realizar estudios que aseguren que la salud de la población no sea afectada por los campos electromagnéticos (Osinergmin, 2017).

Debido al crecimiento demográfico en el país de más de 32 millones de personas, además, del crecimiento de empresas industriales que requieren mayor consumo de energía eléctrica, se han instalado torres de alta tensión que cruzan por las ciudades en todo el país, y por el alto precio de los equipos de medición por ejemplo, la marca NARDA, se ha diseñado e implementado un prototipo que realiza las mediciones a un precio inferior al mercado internacional con el objetivo de proteger la salud de las personas, ya que dichas radiaciones de los campos electromagnéticos de baja frecuencia han sido relacionados a unos posibles efectos sobre la salud, por ejemplo: leucemia infantil, transporte de calcio a través de la membranas celulares, síntesis de ADN potenciada, inhibición de la actividad de los linfocitos, abortos espontáneos, sin que esa comunidad sea informada sobre las normativas y los efectos que provocan esas radiaciones.

Por lo tanto, este prototipo al ser accesible serviría al gobierno local a realizar las mediciones de los campos electromagnéticos, comprobando si estos están por debajo de los límites máximos permisibles.

Justificación

Justificación teórica

La especie humana vive expuesto a campos electromagnéticos naturales, por ejemplo, el campo geomagnético y los fenómenos ondulatorios electromagnéticos atmosféricos. Ahora se considera los campos electromagnéticos producidos por la actividad humana. En un principio estos estaban referidos a las torres eléctricas, algunos aparatos electrodomésticos, usos industriales específicos y los radares. En los últimos años ha incremento fuentes de campos electromagnéticos se ha usado en la industria, la medicina, el comercio, el grado de producción ha alcanzado niveles tales que los expertos alertan de una contaminación electromagnética ambiental. Si esto es así es obvio que incidan de algún modo sobre la salud humana.

Entonces la investigación busca ayudar a conocer mejor los posibles efectos de la salud de los seres humanos que vive expuesto a los campos electromagnéticos producidos por las antenas, líneas de energía eléctrica, etc.

Justificación práctica

Debido al alto costo de los equipos comerciales por marcas reconocidas se diseñará e implementará el prototipo de medidor de campos electromagnéticos de baja frecuencia, contribuyendo con el desarrollo tecnológico del Perú y siendo más accesible para instituciones del estado como Ministerios, universidades y otros. Por lo tanto se podrá corroborar si los campos electromagnéticos irradiados por las torres de energía eléctrica, equipos médicos e industriales cumples con los límites máximos permisibles, como también ayudará con futuras investigaciones sobre las radiaciones no ionizantes.

Objetivos

Objetivos generales

- ❖ Diseñar e implementar un prototipo medidor de campo eléctrico y magnético de baja frecuencia.

Objetivos específicos

- ❖ Diseñar e implementar las sondas de los campos magnéticos y eléctricos.
- ❖ Diseñar e implementar la parte inteligente de ambos módulos para el procesamiento, almacenamiento de datos y comunicación entre ellas mediante fibra óptica.
- ❖ Realizar las pruebas de operación del equipo de exposición y contrastar con el equipo NARDA EFA 300.
- ❖ Accesibilidad de un equipo de bajo costo con seguridad en la medición los campos electromagnéticos de baja frecuencia.

Capítulo 2

Marco teórico

Antecedentes

Antecedentes nacionales

Instituto Nacional de Investigación y Capacitación de Telecomunicaciones – INICTEL UNI (2010), se diseñó e implementó un equipo medidor de campos electromagnéticos de baja frecuencia (60 Hz) de bajo costo para realizar el monitoreo de radiaciones no ionizantes. En todo el proceso de desarrollo del prototipo se tuvo como referencia al equipo NARDA EFA 300 que es un analizador de campos electromagnéticos de baja frecuencia, lo que se quiso realizar es un equipo que tenga la misma funcionalidad que el equipo mencionado. Este diseño se conformó de tres componentes principales: sonda de campo eléctrico, sonda de campo magnético, un equipo procesador de datos. La fabricación de la sonda del campo magnético se compone de 3 lazos de bobinas para una medición isotrópica del campo magnético. Para el caso de la sonda del campo eléctrico solo se fabricó un par de placas paralelas para un solo eje y el procesador de datos se diseñó luego de la fabricación de las sondas para realizar las pruebas respectivas.

Antecedentes Internacionales

Lunca et al. (2008), presenta un instrumento de un solo eje para medir campos magnéticos de baja frecuencia de hasta 200 µT. Consiste en un sensor de bucle externo, un front-end analógico (AFE) y un módulo de adquisición de datos desarrollado en torno a un potente microcontrolador PIC. También se ha desarrollado un software para el registro de datos a través de la interfaz USB. El instrumento puede utilizarse principalmente para evaluar la exposición humana a campos magnéticos. Por otra parte, los campos magnéticos de baja frecuencia, como los producidos por las líneas de alta tensión y las unidades de visualización de vídeo, normalmente requieren dos medidores de campo, uno trabajando en el ancho de banda de frecuencia de 20 Hz a 2 kHz y el otro trabajando desde 2 kHz a unos pocos cientos de kHz. Esta es la razón por la que los autores desarrollaron un medidor de campo de un solo eje que cubre solo el amplio rango de 40 Hz a 150 kHz.

Rioult et al. (2009), en la actualidad existen una amplia variedad de terminales para los usuarios ambulantes. En general, estos terminales proporcionan comunicación inalámbrica que funciona a frecuencias entre uno y unos pocos GHz. Por razones técnicas, incluyendo el acceso múltiple al canal de comunicación y la autonomía de la batería, estos terminales sólo transmiten durante períodos muy cortos, es decir, ráfagas de transmisión. Para una observación directa de ciertas características de las señales transmitidas radiadas por dichos terminales, sólo existen unas pocas configuraciones de medición. Este artículo propone un instrumento de medida de campo electromagnético 3D en tiempo real con visualización directa. El prototipo utilizado para la validación se basa en una serie de sondas conectadas regularmente en un bucle rígido no conductor que se pone en rotación rápida alrededor del terminal bajo prueba.

A. Hanna et al. (2009), en este artículo describen el desarrollo de un "gaussmeter VLF" triaxial, que puede hacerse portátil. Este sistema electrónico puede utilizarse para monitorear la radiación electromagnética VLF en entornos residenciales y ocupacionales. El "gaussmeter VLF" se basa en un microcontrolador con un convertidor A / D incorporado de l0-bit y ha sido diseñado para medir la densidad y frecuencia de flujo magnético a través del ancho de banda VLF (BW). Se utiliza una resolución digitalizada de 0,2 mG para el rango de 0-200 mG y se usa una resolución de 2 mG para el rango de 2-2000 mG. El medidor ha sido diseñado con las siguientes características: 1) rango automático o manual selección de frecuencias; 2) registro de datos; 3) modo de un solo eje; 4) retención de pico; 5) Puerto de comunicación RS-232; Y 6) salida del registrador analógico.

Mario Alberto González Muñoz (2011), describe el diseño y construcción de un equipo prototipo para la medición de campos homogéneos sinusoidal con frecuencia de trabajo de 60 Hz, usando como principal herramienta un sensor de efecto hall. El medidor cuenta con tres fases de construcción, configuración de sensor de efecto hall, programación del microcontrolador y visualización en pantalla. La configuración del sensor cuenta con 2 etapas, filtrado de la señal de alimentación a la bobina Helmholtz y calibración del sensor de efecto hall.

Lunca et al. (2014), en este trabajo se presenta un instrumento de un solo eje para medir campos magnéticos de baja frecuencia de hasta 200 µT. Se compone de un sensor de bucle externo, un front-end analógico (AFE) y un módulo de adquisición de datos desarrollado alrededor de un poderoso microcontrolador PIC. También han desarrollado un software para el registro de datos a través de la interfaz USB. El instrumento puede utilizarse principalmente para evaluar la exposición humana a campos magnéticos.

Bohari et al. (2014), menciona que los campos electromagnéticos (CEM) producen un enorme impacto en cualquier sociedad moderna. Se sabe que un campo electromagnético fuerte puede causar efectos agudos, tales como quemaduras. Los mecanismos detrás de estos efectos son sostenibles. Sin embargo, el efecto sobre la exposición a largo plazo a los campos débiles puede resultar perjudicial a la salud. Debido a que las exposiciones son generalizadas, incluso los pequeños efectos sobre la salud pueden tener profundas implicaciones para la salud pública. Ese trabajo consto en diseñar e implementar un detector de campo electromagnético (EMF) que puede detectar la radiación. Estos EMF se encuentran en las radiaciones de los rayos ultravioleta, rayos gamma, rayos X y etc. El sensor EMF descrito, mide el rango de radiación en muy baja frecuencia en el rango de 50 Hz. Los circuitos pueden evaluar el rango de radiación de la fuente EMF, tal como toma de corriente eléctrica cuando se cambió a través del indicador LED. La pulsación de las radiaciones se puede visualizar a través del parpadeo de los LEDs. Este trabajo presenta el principio de funcionamiento del sensor, el diseño del proyecto y los datos del sensor de procesamiento, y algunos resultados experimentales preliminares. Se utilizó el software Proteus para diseñar y simular el circuito y luego proceder con el hardware basado en el circuito de Proteus.

Definiciones

Radiaciones

Se puede decir que la unidad de radiación electromagnética es el fotón, estos se diferencian por su frecuencia; la cantidad de fotones de los rayos ultravioletas es mayor que los de infrarrojos, y menor que los rayos X. Entonces a mayor frecuencia implica mayor energía. Por lo tanto la radiación significa energía transmitida por ondas, cuyo movimiento sinuoso se define como propagación en un medio físico (Usca, 2010).

Campos electromagnéticos

Nuestro entorno siempre ha sido expuesto este tipo de radiación como resultado de la actividad solar, los cambios meteorológicos y la actividad de la biosfera. Los campos electromagnéticos de hoy en día también son generados por sistemas artificiales tales como las líneas de transmisión de alta potencia, equipos eléctricos y sistemas de comunicaciones (OMS, 2018) .

El principal efecto biológico de los campos electromagnéticos es el calentamiento, sin embargo las personas están expuestas a niveles de radiaciones menores de lo indicado en las normativas (OMS, 2018).

Las ondas electromagnéticas se caracterizan por los siguientes parámetros:

- Frecuencia (f),
- Longitud de onda (λ)
- Intensidad de campo eléctrico
- Intensidad del campo magnético

- Polarización eléctrica (P)
- Velocidad de propagación (c)
- Vector de poynting (S)

Estás pueden ser transmitidas por el espacio libre o por un material característico y beneficio en su transmisión, la forma propagación en espacios libres dependerá de la frecuencia que viaja dicha onda (OMS, 2018).

Estos campos electromagnéticos comprenden una gama de frecuencias, desde muy bajas hasta frecuencias muy altas. En la figura 1 se aprecia el espectro electromagnético y los servicios que se brindan en cada una de ellas.

Figura 1. Espectro electromagnético
Fuente: Actualidad Informática (2011)

Diferencias entre los campos electromagnéticos ionizantes y no ionizantes

La longitud de onda y la frecuencia son una de las características más importante de los campos electromagnéticos. Las ondas electromagnéticas se transportan por partículas llamadas cuantos de luz. Los cuantos de luz de ondas con frecuencias más altas (longitudes de onda más cortas) transportan más energía que los de las ondas de menor frecuencia, ósea, longitudes de onda más larga (OMS, 2018).

Algunas ondas electromagnéticas transportan tanta energía por cuanto de luz que son capaces de romper los enlaces entre las moléculas. De las radiaciones que componen el espectro electromagnético, los rayos gamma que emiten los materiales radioactivos, los rayos cósmicos y los rayos X tienen esta capacidad y se conocen como «radiación ionizante». Las radiaciones compuestas por cuantos de luz sin energía suficiente para romper los enlaces moleculares se conocen como radiación no ionizante (OMS, 2018).

Las fuentes de campos electromagnéticos generadas por el hombre que constituyen una parte fundamental de las sociedades industriales (la electricidad, las microondas y los campos de radiofrecuencia) están en el extremo del espectro electromagnético correspondiente a longitudes de onda relativamente largas y frecuencias bajas y sus cuantos no son capaces de romper enlaces químicos (OMS, 2018).

Campo cercano y campo lejano

Entre los factores a considerar en un diseño de un nuevo prototipo se debe saber si el generador de EMI está en la zona de campo cercano o de campo lejano. Debido a la complejidad de los campos electromagnéticos se tiene dificultades en la medición de estas, dicho de otra menara, estos campos dependen de la zona que está establecido la onda de la fuente de la radiación (Sosa Pedroza, Carrión Rivera, Martínez Zuñiga, & Peña Ruiz, 2014).

Existen tres regiones según la distancia entre el punto de medición y la fuente de radiación. Se puede observar la frontera de ambos campos en la figura 2 (Sosa Pedroza, Carrión Rivera, Martínez Zuñiga, & Peña Ruiz, 2014).

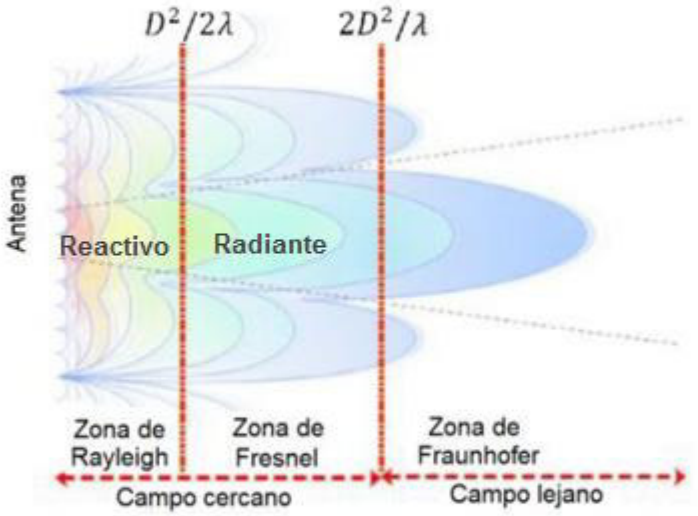

Figura 2. Deformación del campo en función de la diferencia de fase de fuentes puntuales. Fuente: Una propuesta para transformar mediciones de campo cercano a campo lejano (2014)

Región de campo cercano. Se encuentra la región de Fresnel y la región reactiva, generalmente está situada cerca de una antena u otra estructura radiante. Los campos eléctricos y magnéticos no son de tipo onda plana (UIT-T, 2011) .

La región de campo cercano se subdivide todavía en la región de campo cercano reactivo y la región de campo cercano radiante (UIT-T, 2011). La predominancia de un campo dependerá del nivel de intensidad eléctrica, baja tensión de ella.

Región de campo lejano. Llamada también región de fraunhofer, en esta región, el campo es de tipo onda plana, es decir, el campo eléctrico y el campo magnético se transportan en la misma dirección de propagación. El cociente entre la intensidad de campo eléctrico y campo magnético es la constante llamada impedancia de espacio libre (UIT-T, 2011).

Impedancia de espacio libre (Z_0). Se define como la raíz cuadrada de la permeabilidad del espacio libre μ_0 dividida por la permitividad en el vacío ε_0 (UIT-T, 2011, p.3).

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 120\pi \,.\Omega \approx 377\ \Omega$$

El campo equivalente, al ser el campo eléctrico y el campo magnético magnitudes vectoriales, se define como:

$$E_e = \sqrt{E_x^2 + E_y^2 + E_z^2}$$

$$H_e = \sqrt{H_x^2 + H_y^2 + H_z^2}$$

Donde:

E: Campo eléctrico

H: Campo magnético

Se concluye que realizar mediciones en campo cercano es complejo, debido que no existe una relación directa de estos campos, en consecuencia se tiene que medir ambos campos por separados, es decir dos elementos sensores. La propagación de los campos electromagnéticos en campo lejano está en la figura 3 (Pérez Vega, Sáinz de la Maza, & Casanueva López, 2007).

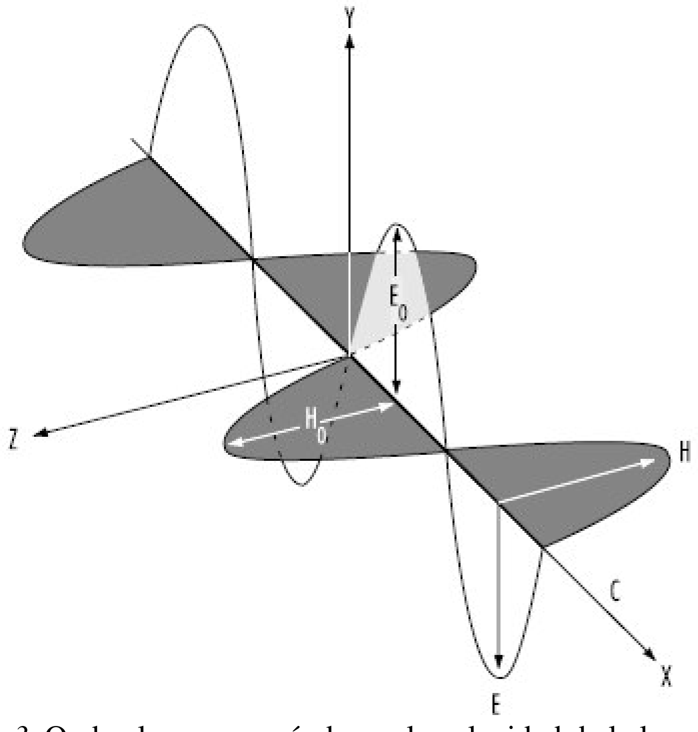

Figura 3. Onda plana propagándose a la velocidad de la luz
Fuente: Radiaciones no ionizantes (2012)

Permeabilidad y Permitividad

Permeabilidad. Es un parámetro físico que describe como un material afecta y es afectado por un campo magnético, es decir, es la capacidad de una sustancia o medio para atraer y hacer pasar a través de ella campos magnéticos (Vidal, 2013).

Este es dependiente de los parámetros como la temperatura, frecuencia, dirección e propagación, se define como:

$$\mu^* = \mu_0 \mu_r^*$$

Donde:

μ^* : *Permeabilidad eléctrica*

μ_0: *Permeabilidead del medio en el vacío* ($4\boldsymbol{\pi}$ x10^{-7} H/m)

μ_r^* : *Permeabilidad relativa*

La permitividad (o impropiamente constante dieléctrica). Es una constante física que describe cómo un campo eléctrico afecta y es afectado por un medio. La permitividad del vacío es $8{,}85418781\ x\ 10^{-12} F/m$.

La permitividad está determinada por la tendencia de un material a polarizarse ante la aplicación de un campo eléctrico y de esa forma anular parcialmente el campo interno del material. Está directamente relacionada con la susceptibilidad eléctrica (Vidal, 2013).

Entonces la relación que existe entre la permitividad eléctrica en el vacío y en un material se observa en la siguiente ecuación:

$$\boldsymbol{\varepsilon} = \frac{\boldsymbol{\varepsilon_o}}{\mathbf{k}}$$

Donde:

ε: Permitividad de un material

$\boldsymbol{\varepsilon_o}$: *Permitividad en el vacío*

K: Constante dieléctrica de un material.

Constantes físicas

Estas cantidades, unidades y constantes se muestran en las tablas 2 y 3. La cuales, son las que se usaran en el diseño del prototipo.

Tabla 2 Unidades

Cantidad	Símbolo	Unidad	Dimensión
Densidad de corriente	J	amperes por metro cuadrado	A/m^2
Intensidad de campo eléctrico	E	voltios por metro	V/m
Densidad de flujo eléctrico	D	culombios por metro cuadrado	C/m^2
Frecuencia	f	hercios	Hz
Intensidad de campo magnético	H	amperes por metro	A/m
Densidad de flujo magnético	B	tesla (Vs/m^2)	T
Permeabilidad	μ	henrios por metro	H/m
Permitividad	ε	faradios por metro	F/m
Longitud de onda	λ	Metro	m

Tabla 3 *Constantes físicas*

Constante física	Símbolo	Magnitud
Velocidad de la luz en el vacío	c	2 99 × 108 m/s
Permitividad de espacio libre	ε0	$8\ 85 \times 10^{-12}$ F/m
Permeabilidad de espacio libre	μ0	$4\pi \times 10^{-7}$ H/m
Impedancia de espacio libre	*Z*0	377 ohmios

Medidores de campos

Estos miden la energía radiada por una fuente de campos electromagnéticos, dentro del ancho de banda por el cual se diseñó. Estos generalmente se componen de uno o dos sensores isotrópicos dependiendo el ancho de banda de trabajo, un medidor, una línea de transmisión eléctrica u óptica.

Estos se pueden clasificar según la frecuencia de propagación

Medidores de baja frecuencia

Estos por su complejidad de medición y la propagación de los campos electromagnéticos, se requiere una sonda para cada tipo de campo. En campo cercano estos campos no se encuentran acoplados por ende habrá una relación directa de estos campos para obtener la magnitud a través del otro (Molero Castejón, 2013).

Medidor de baja frecuencia para campo eléctrico

Las medidas del campo eléctrico en esta gama de frecuencias son muy complejas, debido que al estar situado una persona u objeto cerca al medidor, esté obtendrá datos no coherentes. Frente a esta dificultad es recomendable usar como línea de transmisión la fibra óptica, ya que esta es inmune a ruidos eléctricos o cualquier interferencia del ambiente (Molero Castejón, 2013).

El sensor capacitivo formado de placas paralelas, con la electrónica de amplificación y una batería interna, este tipo de sensor mencionado se puede observar en la figura 4 (Molero Castejón, 2013).

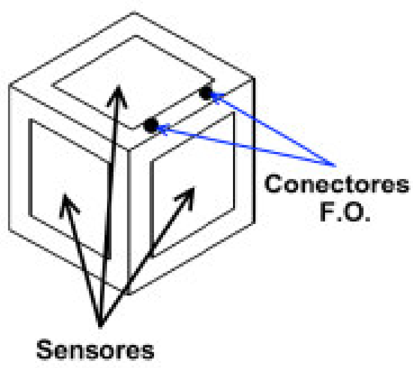

Figura 4. Sensor de campo eléctrico de baja frecuencia
Fuente: Medidor de la intensidad ambiental de campo electromagnético, EFM (2013)

Los sensores tiene una característica partícula y similar a los dipolos, ya que en la selección de su dimensiones se tiene que considerar que las placas deben ser menor a la longitud de onda de una señal medida (Molero Castejón, 2013).

La detección del campo se basa en la medida de la tensión entre las placas de un condensador generado por la corriente de desplazamiento que se encuentra en las placas, esta es generada por el campo eléctrico. Esta corriente pasa por la impedancia del medidor en paralelo y la impedancia del condensador. En ella hay una tensión que se mide para obtener el valor medido del campo **E** como se observa en la figura 5 (Molero Castejón, 2013).

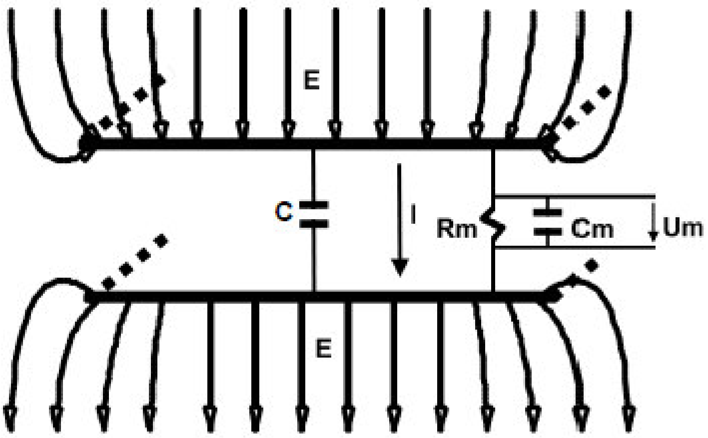

Figura 5. Detección del campo eléctrico
Fuente: Medidor de la intensidad ambiental de campo electromagnético, EFM (2013)

Donde:

E = Campo eléctrico

C = Capacidad en el sensor capacitivo

I = Corriente de desplazamiento entre las placas capacitivas

Rm = Resistencia del medidor

Cm = Capacidad del medidor

A = Área de la placa del sensor

$$I = j\omega\varepsilon \int_A \bar{E}\, d\bar{A}$$

$$U_m = IZ_{eq} = \frac{j\omega\varepsilon \int_A \bar{E}\, d\bar{A}}{\frac{1}{R_m} + j\omega(C + C_m)}$$

Medidor de baja frecuencia para campo magnético

Los medidores de baja frecuencia por lo general constan de una disposición de bobinas isotrópica, un ADC y registrador de datos. En su etapa de adaptación, amplificación y filtrado se pone un filtro pasa alto de 30 Hz para eliminar los efectos del campo magnético (Molero Castejón, 2013).

Estos sensores están basados por la ley de inducción de Faraday, la ley indica, en una bobina hay una tensión debido a la variación de flujo que lo atraviesa (Molero Castejón, 2013).

$$Vin \approx N2\pi fABcos\theta$$

Donde:

N: $número\ de\ vueltas\ de\ la\ bobina$

f: $Frecuencia\ del\ campo\ magnético\ que\ atraviesa\ la\ bobina$

A: $Área\ transversal\ de\ la\ bobina$

B: $Densida\ de\ flujo\ \ magnético$

θ: $Ángulo\ entre\ el\ plano\ de\ la\ bobina\ y\ el\ flujo\ del\ campo\ magnético$

Tanto A como N son valores constantes pero es necesario corregir la dependencia con el ángulo y la frecuencia para tener mediciones isotrópicas (Molero Castejón, 2013).

La dependencia del ángulo se corrige implementando 3 bobinas, cada una perpendicular a las otras (isotrópica), la figura 6 muestra la disposición de las 3 bobinas para cada eje (Molero Castejón, 2013).

La dependencia con la frecuencia se corrige instalando un integrador RC de valor adecuado para anular la parte compleja de la impedancia dentro la frecuencia de funcionamiento (Molero Castejón, 2013).

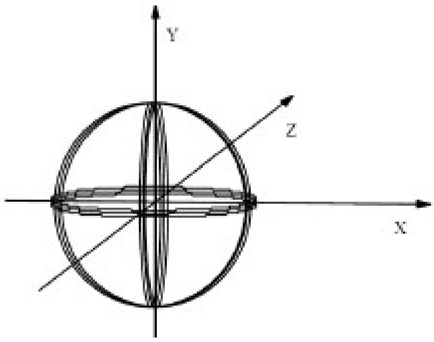

Figura 6. Disposición isotrópica de la bobina
Fuente: Medidor de la intensidad ambiental de campo electromagnético, EFM (2013)

Es necesario considerar que esos hilos de metálicos se encuentres apantallados, ya que estos pueden servir como antenas.

Conceptos para el diseño de los sensores y protocolos de transmisión de datos

Leyes físicas usadas en la medición del campo magnético

Ley de inducción de Faraday

Según la literatura física, se sabe que un corriente genera una circulación de campo magnético y lo mismo sucede de manera inversa. De acuerdo a la ley de Faraday, se genera una fuerza electromotriz en un circuito cerrado cuando existe una variación de flujo del campo magnético en el tiempo sobre ella.

Entonces la ley de Faraday tiene la siguiente forma: La fuerza electromotriz (fem) es directamente proporcional al cambio del flujo del campo magnético que atraviesa la superficie (Área) que encierra la espira.

De acuerdo lo que indica la ley de Faraday se usará un elemento sensor isotrópico de bobinas, en la figura 7 se tiene un boceto del sensor de bobina.

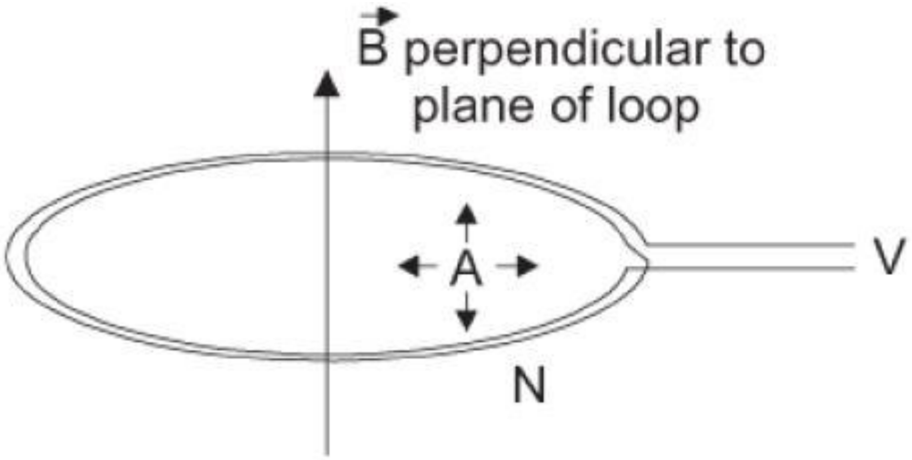

Figura 7. Sensor de lazo de bobina donde el número de vueltas N.
Fuente: Very low frequency electromagnetic field detector with data acquisition (2009)

El voltaje Vin o la fuerza electromotriz se induce a lo largo de la longitud de una bobina.

$$V_{in} = -N \left(\frac{d\emptyset}{dt}\right) \qquad (1)$$

$$V_{in} = R \, . I_{in}$$

Sea:

$$\emptyset = \int_S B.dS \quad (2)$$

Donde:

N: Número de vueltas

ϕ: Flujo magnético

La ecuación (1) puede ser reescrito para un sensor de bucle de un diámetro “d”.

$$V_{in} = -\frac{N\pi d^2}{4} \, . B_0 j \, \omega e^{j\omega t} \qquad (3)$$

Donde:

B_0: Amplitud de la densidad de flujo magnético

ω: Frecuencia en radianes

Considerando solamente la magnitud de la ecuación (3)

$$V_{in} = |V_{in}| = \frac{N\pi d^2 B_0 \omega}{4} = \frac{2N\pi^2 d^2 f}{4} . B_0 \qquad (4)$$

Resolviendo y despejando N, tenemos:

$$N = \frac{V}{2\pi f B_0 A} \quad (5)$$

A partir de la ecuación (4), la sensibilidad puede expresarse de la siguiente manera:

$$Sensibilidad = \frac{V}{B_0} = 2\pi f N A \qquad (6)$$

Ley de Bio y Savart

Consideremos un alambre, que transporta una corriente I como la figura 8 se muestra.

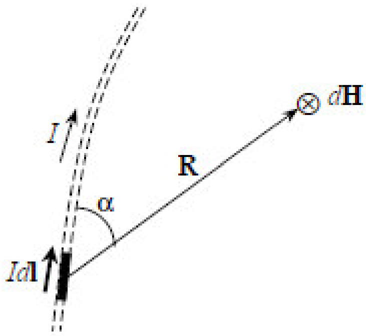

Figura 8. Cable infinito en el espacio.
Fuente: Fundamentos de Teoría Electromagnética (2013)

Luego Bio y Savart hace mención lo siguiente. Nos dice que una contribución infinitesimal del campo magnético en el punto P será:

$$B_p = \frac{\mu_0}{4\pi} \frac{Id\bar{l} \, x \, \hat{r}}{r^2}$$

Esa contribución es proporcional a la corriente, su carácter vectorial es perpendicular tanto al vector diferencial de longitud del alambre respecto al vector unitario de posición $\hat{r}$ e inversamente proporcional a la cuadra de la distancia.

$$d\vec{l} \, x \, \hat{r} = dl \, (1) sen \, \alpha$$

Por lo tanto

En tamaño, una pequeña contribución

$$B_p = \frac{\mu_0}{4\pi}\frac{Idl\ sen\alpha}{r^2}$$

Donde:

u_0 es la permeabilidad del medio en el vacío con valor de 4**π** x10^{-7} (H/m)

Ley de Ampere

La ley de Ampere describe matemáticamente el campo magnético, el campo magnético es una manifestación del campo eléctrico cuando se incluye movimientos relativos entre las fuentes. En el caso de configuraciones simples de corriente, la ley de Ampere describe cómo la fuente principal del campo magnético son cargas eléctricas en movimiento, es decir, la fuente es la corriente eléctrica (Serway, 2001).

Teniendo como ejemplo un alambre rectilíneo, este crea circunferencias de campo magnético constante alrededor del alambre y como se tiene un campo en cada circunferencia se halla la integral de línea a lo largo de cada circunferencia como se muestra en la figura 9. Entonces este es igual a la intensidad de corriente circulante por el alambre y multiplicada por una constante, que es la permeabilidad magnética (Serway, 2001).

$$\oint_c \vec{B}.d\vec{l} = \mu_0.i_{enc}$$

Donde:

B: campo magnético

dl: segmento infinitesimal del trayecto de integración

μ_0: permeabilidad del espacio libre

Ienc: corriente entrada por el trayecto

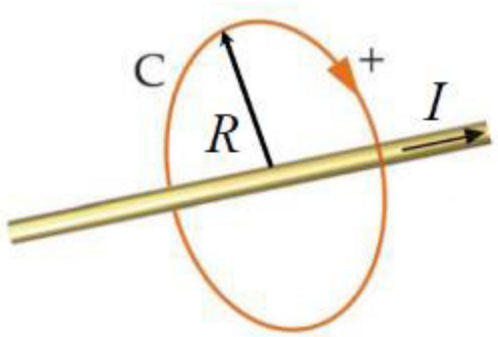

Figura 9 Representación del campo magnético en un alambre rectilíneo.
Fuente: Electricidad y Magnetismo. Luz. Física Moderna (tipler, 2005)

Leyes físicas usadas en la medición del campo eléctrico.

Ley de Coulomb

Está ley nos hace mención a la medición de la interacción entre cargas puntuales. En la figura 10 se observa que r1 y r2 son los vectores de posición de Q1 y Q2 respectivamente. Por lo tanto el vector R12 = r2 – r1, la cual representa la de recta entre los puntos Q1 a Q2 (cargar de prueba). El vector F12 interactuará en el punto Q2 debido a la interacción con Q1 y en la figura 10 se muestra un ejemplo para cargas que tienen igual polaridad. Por lo tanto la ley de Coulomb puede ser representara en la siguiente ecuación: (Moron, 2013)

$$F = \frac{KQ_1Q_2}{R_{12}^2}\,\widehat{a_{12}}$$

Donde $\widehat{a_{12}}$ es un ventor unitario en la dirección de R12, sea:

$$\widehat{a_{12}} = \frac{R_{12}}{|R_{12}|} = \frac{r_2 - r_1}{|r_2 - r_1|}$$

Esta ecuación reemplazada en la primera, se obtiene:

$$F = \frac{Q1Q2}{4\pi\varepsilon_0}\frac{r_2 - r_1}{|r_2 - r_1|^3}\,\widehat{a_{12}}$$

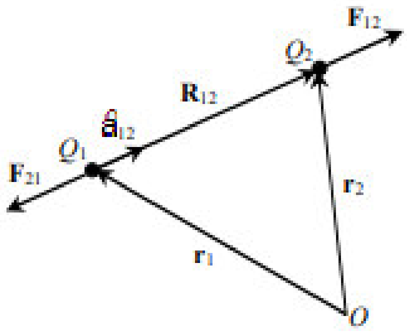

Figura 10 Fuerza entre dos cargas eléctricas.
Fuente: Fundamentos de teoría electromagnética (2013)

Se aplica el principio de superposición, donde las fuerzas ejercidas sobre una carga Q por otras N cargas, por ejemplo, Q1, Q2,…, QN, entonces los vectores de posición son r1, r2,…, rN (Moron, 2013). La suma vectorial es:

$$F = \frac{Q}{4\pi\varepsilon_0}\sum_{K=1}^{N} Q_K \frac{(r - r_K)}{|r - r_K|^3}$$

La intensidad del campo eléctrico se expresa:

$$E = \lim_{Q\to 0}\frac{F}{Q} = \frac{F}{Q}$$

$$E(r) = \frac{1}{4\pi\varepsilon_0}\sum_{K=1}^{N} Q_K \frac{(r - r_K)}{|r - r_K|^3}$$

$$K = 9\,x\frac{10^9 F}{m} = \frac{1}{4\Pi\varepsilon o} = Cte\ de\ proporcionalidad$$

Dónde:

ε_0: Permitividad del vacío, 8.854 x 10^{-12} F/m

Ley de Gauss

La ley de gauss permite interpretar como se comporta el campo eléctrico alrededor de las cargas o densidad de cargas. Esta ley es eficiente que la ley de coulomb. Se puede resumir en flujo eléctrico saliendo de una superficie cerrada es igual a la carga encerrada sobre la permitividad del vacío o algún material (Moron, 2013).

$$\emptyset = \text{flujo} = \frac{Q}{\varepsilon_o}$$

$$\emptyset: \text{N.m2/ C}$$

El flujo eléctrico es la cantidad de energía en forma de campo eléctrico que paso sobre una superficie. Considerar un punto cualquiera, el elemento ΔS de la superficie y que D genera un ángulo Θ en ΔS y se observa en la figura 11, según el grafico se observa que el flujo cruza la superficie ΔS, por lo tanto el flujo es el producto entre los componentes de la normal de D y ΔS (Moron, 2013).

$$\Delta\emptyset = \text{flujo} \,.\, \Delta S = D_{\text{normal}}\, \Delta S = D\cos\Theta\, \Delta S = D.\Delta S$$

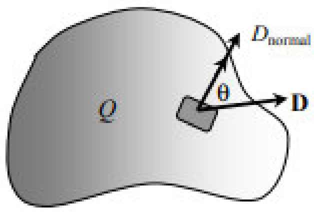

Figura 11. Flujo eléctrico por una superficie ΔS
Fuente: Fundamentos de teoría electromagnética (2013)

Por lo tanto, el flujo total se representa de la siguiente manera:

$$\emptyset = \oint_S D.dS = \text{carga encerrada} = Q_{enc}$$

$$Q_{enc} = \sum_k Q_k$$

La suma de todas las cargas puede ser lineal, superficial o volumétrica, se expresa de la siguiente forma:

$Q_{enc} = \int_L \rho_l dl$, lineal

$Q_{enc} = \int_s \rho_s ds$, superficial

$Q_{enc} = \int_v \rho_v dv$, volumétrica

Medición por Potencial Eléctrico.

La manera de obtener el campo eléctrico (E) se usará del potencial escalar eléctrico V. Esta forma de calcular el campo eléctrico (E) se usará ya que se trabajará con escalares. Se tiene una carga Q que se quiere mover de un punto A hasta un punto B, con una velocidad constante y expuesta a un campo eléctrico como se muestra en la figura 12 (Moron, 2013).

Por la ley de coulomb se sabe que $\mathrm{E} = \lim_{\mathrm{Q}\to 0} \frac{\mathrm{F}}{\mathrm{Q}} = \frac{\mathrm{F}}{\mathrm{Q}}$, entonces el trabajo efectuado por desplazar la carga a una distancia dl es: (Moron, 2013)

$$\mathrm{dW} = -\mathrm{F.dl} = -\mathrm{QE.dl}$$

El signo negativo indica que el trabajo realizado fue es por un agente externo contra el campo, por lo tanto el trabajo total realizado será:

$$\mathrm{W} = -\mathrm{Q}\int_{\mathrm{A}}^{\mathrm{B}} \mathrm{E.dl}$$

Esta cantidad es el potencial entre los puntos A y B y se expresa de la siguiente manera: (Moron, 2013)

$$\mathrm{V_{AB}} = \frac{\mathrm{W}}{\mathrm{Q}} = -\int_{\mathrm{A}}^{\mathrm{B}} \mathrm{E.dl} \qquad \text{V: J/C (volt)}$$

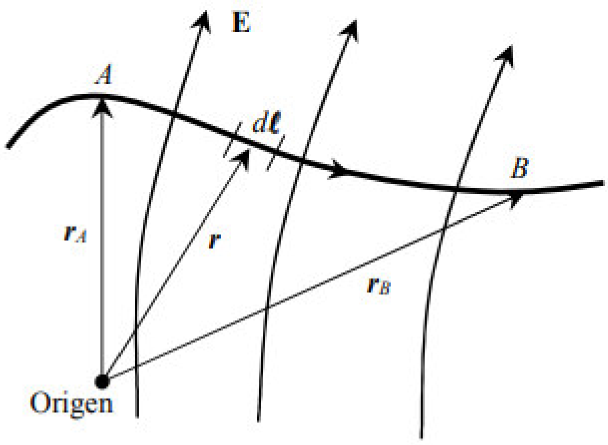

Figura 12 Desplazamiento de una carga.
Fuente: Fundamentos de teoría electromagnética (2013)

Estándar de conexión por fibra óptica – Toslink

TOSLINK ™ es una familia de dispositivos de transmisión de datos que utilizan señales ópticas en lugar de señales eléctricas. Debido a que TOSLINK utiliza un cable de fibra óptica como línea de transmisión, proporciona los siguientes beneficios, en comparación con la transmisión eléctrica que utiliza un cable coaxial o de par trenzado (TOSHIBA, 2008):

- La línea de transmisión (es decir, el cable óptico) no es susceptible a interferencias electromagnéticas.
- El cable óptico no irradia ningún ruido electromagnético.
- El cable óptico proporciona un aislamiento galvánico completo entre los equipos.

Funcionamiento

Un fotoacoplador es un semiconductor que consiste en un dispositivo emisor de luz y un dispositivo receptor de luz moldeado en un paquete. Se usa para proporcionar aislamiento eléctrico entre entrada y salida. Por el contrario, TOSLINK utiliza unidades de emisión de luz y receptoras de luz separadas que están conectadas a través de un cable óptico largo. Debido a que se utiliza un cable óptico como línea de transmisión, es posible transmitir señales a largas distancias mientras se proporciona un aislamiento galvánico entre los extremos transmisor y receptor. Por lo tanto, TOSLINK se puede ver, en cierto sentido, como un fotoacoplador de larga distancia. La diferencia entre ellas se observa en la figura 13. (TOSHIBA, 2008)

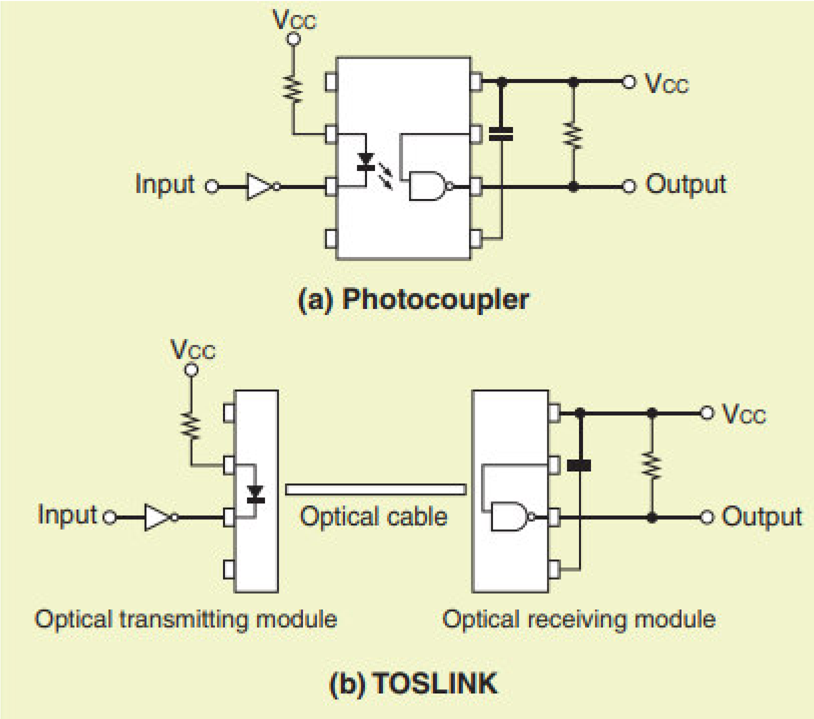

Figura 13 Comparación de un dispositivo Toslink y un fotoacoplador.
Fuente: Fiber-optic Devices Toslink (2008)

El transmisor requiere de un circuito para regular la corriente de LED que conmuta en ON y OFF. En el caso de receptor recibe la luz con un fotorreceptor y a su vez se amplifica la onda.

Sistemas de transmisión eléctricos y ópticos

En un sistema de transmisión de datos eléctricos, un controlador de línea se utiliza para conducir señales eléctricas a través de una línea de transmisión larga, como un cable de par trenzado. En el otro extremo, un receptor de línea compensa la caída de señal amplificando las señales. Se requiere un conector en cada extremo del cable. Por el contrario, en un sistema basado en TOSLINK, un módulo transmisor convierte las señales eléctricas en señales ópticas, y un módulo receptor convierte las señales ópticas en señales eléctricas. Se utiliza un cable de fibra óptica como línea de transmisión y los conectores ópticos unen los módulos de transmisión y recepción al cable. El módulo de transmisión TOSLINK incorpora un diodo emisor de luz y un circuito de control. El módulo de recepción TOSLINK incorpora un fotodiodo y un circuito de remodelación de forma de onda. La diferencia entre ellas se observa en la figura 14. (TOSHIBA, 2008)

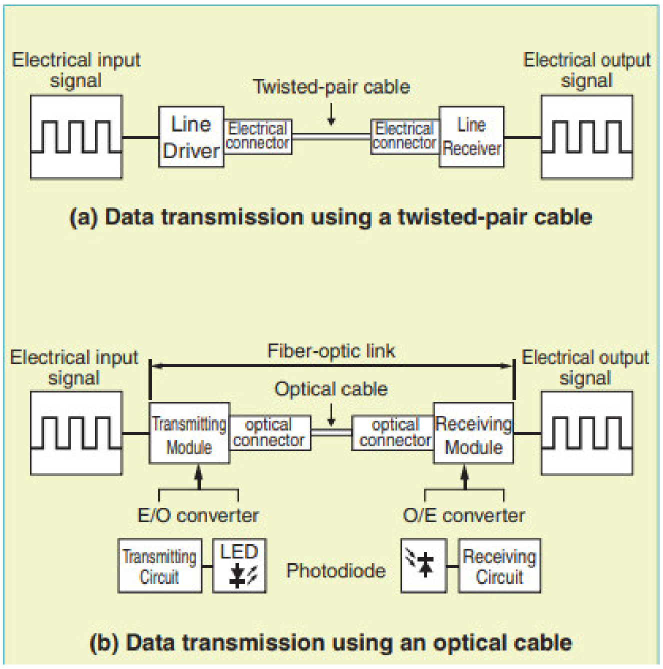

Figura 14 Sistema de transmisión de datos.
Fuente: Fiber-optic Devices Toslink (2008)

Modos de transmisión de datos

Los dos tipos de transmisión que se pueden considerar son serie y paralelo.

Transmisión en serie. La comunicación serie consiste en el envío de bits de data de manera secuencial a través de una línea (Martinez, 2007).

En la transmisión en paralelo, los bits que representan la data son transmitidos de forma paralela. Si una data consiste de diez bits, por lo tanto, la transmisión en paralelo se requiere de diez líneas (Martinez, 2007).

La transmisión serial es más lenta que la paralela debida que se transmite un bit a la vez. Una ventaja entre la transmisión serial y paralelo es el consto de implementación. Estos costo se hará más notorio cuando se realiza las transmisiones a larga distancia (Martinez, 2007).

Sincronización en la transmisión

Cuando se transmite información a través de una línea serie se requiere usar sistemas de codificación que permitan resolver los problemas de sincronización (Herrera Pérez, 2010).

Sincronización de bit. El receptor requiere conocer dónde empieza y dónde termina el tiempo dedicado a transmitir cada bit en la señal recibida para efectuar el muestreo de la misma en el centro de la celda de bit. Considérese el caso de la transmisión en serie de la información 101010101. Si se utiliza una codificación NRZ (no retorno a cero), los bits 1 y 0 indican niveles lógicos alto y bajo respectivamente. La señal en la línea y su componente de reloj será la representada en la figura 15 (Herrera Pérez, 2010).

En la figura se puede observar varios bits consecutivos e iguales de modo que la línea no efectúa ninguna transición y el receptor tendrá la referencia de dónde empieza y termina cada bit (Herrera Pérez, 2010).

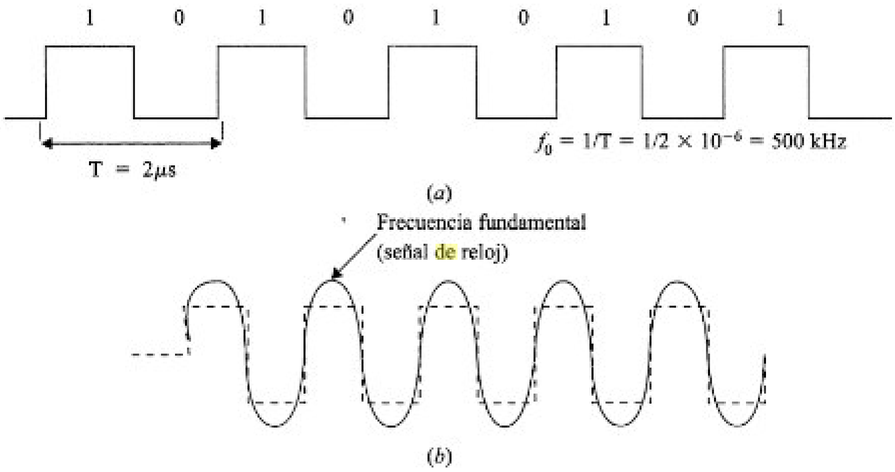

Figura 15 Señal de datos y su componente de reloj
Fuente: tecnologías y redes de transmisión de datos (2010)

Sincronización por palabra. La información en serie se transmite bit a bit, pero la misma sólo tiene sentido en palabras de un determinado número de bits (Herrera Pérez, 2010).

Protocolo de transmisión de datos - Comunicación asíncrona

El receptor/transmisor asíncrono universal (Universal Asynchonous Receiver/Transmitter, UART) es importante para los sistema de comunicaciones serie. La función principal de este dispositivo es cambiar los datos de serie a paralelo e inversamente, para el caso de recepción este dispositivo convierte los datos seriales a paralelos y en la transmisión de la forma inversa. UART es denominado universal debido que es configurable el formato y la velocidad de transmisión de los datos (Martinez, 2007).

En la figura 16 se muestra el esquema general con los bloques básicos de un UART.

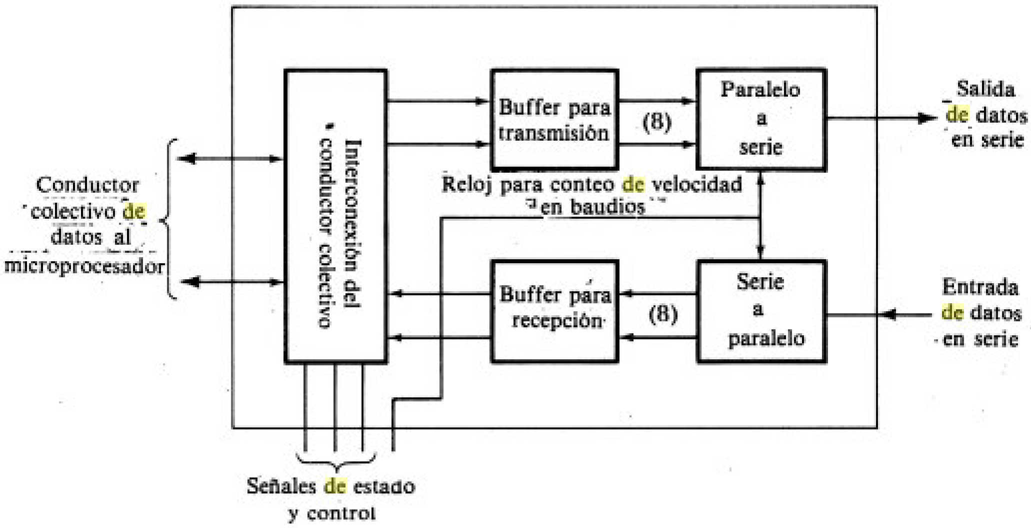

Figura 16. Diagrama de bloques funcionales de un UART
Fuente: Introducción a los microprocesadores. Equipos y Sistemas (2010)

El UART transmite bits individuales de forma secuencial. El receptor tiene la función de reensamblar estos bits en un byte completo. Evidentemente la transmisión de datos a través de una sola línea es menos costosa que una transmisión en paralelo (Martinez, 2007).

El envío de un carácter se completa con la secuencia mostrada en la siguiente figura 17.

En los transmisor y el receptor se encuentran los componentes, las cuales son: un generador de reloj que puede muestrear cada bit transmitido por ser múltiplo de la velocidad de transmisión (bit rate), dos registros con desplazamientos, sistema de control, la lógica para el control de escrituras, los buffers para el transmisor y el receptor, los buses paralelos y una memoria. (Díaz Mula, s.f)

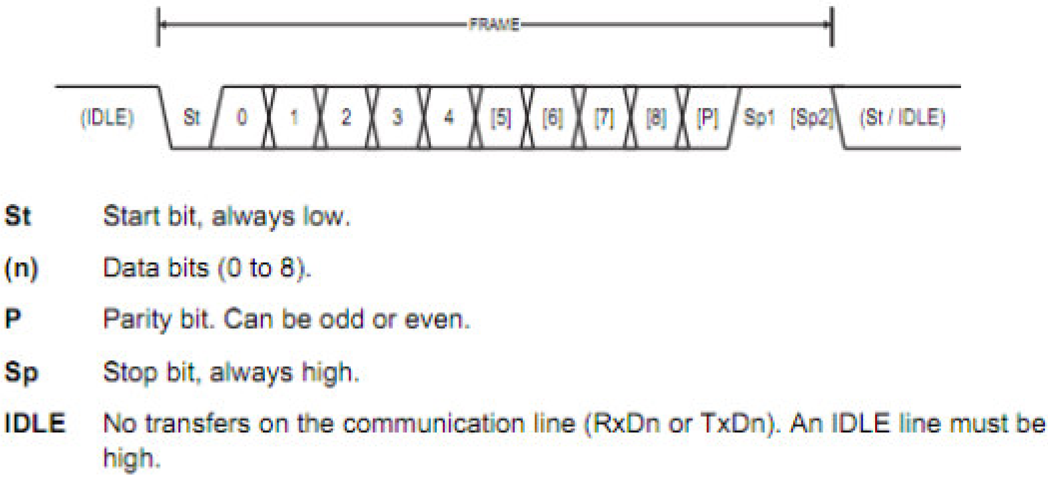

Figura 17. Transmisión de datos a través de la UART
Fuente: Universal Asynchronous Receiver-Transmitter (s.f)

Equipo de referencia

NARDA EFA 300

El analizador de campo EFA-300 es un dispositivo que sirve para monitorear campos de baja frecuencia en el rango de 0.5 Hz a 32 kHz.

Todas las funciones de este instrumento están diseñadas para facilitar su uso en condiciones prácticas. La operación se ha organizado para que el instrumento se pueda configurar de la manera más simple posible con las teclas de función y las teclas de menú. Las teclas de menú se usan para cambiar entre los cuatro menús principales: MODE, CONF, MEM y USUARIO. La tecla MODE brinda acceso hasta 5 modos de operación diferentes. La tecla MEM permite grabar un conjunto de mediciones controladas por temporizador y recuperar los resultados almacenados según sea necesario. La tecla CONF permite el acceso a funciones adicionales tales como la activación de una alarma, la entrada de información de fecha y hora o la selección de curvas de valores límites almacenados.

Este equipo realiza la medición de ambos campos, sea magnético como eléctrico, las mediciones de campo eléctrico son posibles cuando se conecta la Unidad Básica y la Unidad de medidor de campo eléctrico mediante un cable de fibra óptica, el medidor de campo eléctrico tiene forma de cubo formado por placas alineados con precisión como se observa en la figura 18. Esto permite que la Unidad de Campo Eléctrico altamente sensible funcione a distancia para garantizar que los efectos en el campo causados por el operador no influyan en la medición.

Figura 18. Sonda de campo eléctrico
Fuente: Operating Manual Narda Safety Solutions (2005)

En las mediciones del campo magnético, la sonda de prueba $\vec{B}$ se utiliza para medir campos magnéticos. Hay tres tipos de sondas diferentes disponibles para usar en diferentes entornos o para diferentes propósitos de medición.

- Sonda interna de campo B

La sonda de campo B interna se usa cuando los campos se deben detectar y medir con un mínimo de trabajo y precisión de medición de 6% aproximadamente.

- Sonda externa de campo B con diámetro de 3 cm

Esta pequeña sonda de campo B se puede utilizar para realizar mediciones precisas en lugares estrechos o de difícil acceso y precisión de medición de 6% aproximadamente.

- Sonda de campo B de precisión externa con área de sección transversal de 100 cm2

Una sonda con un área efectiva de sección transversal de 100 cm2. La gran superficie elimina los efectos de pequeños campos de remolino y garantiza mediciones de alta precisión.

La sonda del campo magnético está constituida por 3 bobinas ortogonales como se observa en la figura 19, la cual el voltaje inducido que se obtiene en cada bobina se usa para hallar el flujo magnético en cada eje. Ese voltaje se digitaliza y pasa por una etapa de procesamiento de señales realizando el filtrado de señales no requeridas.

Figura 19. Sondas del campo magnético de diferentes diámetros.
Fuente: Operating manual Narda Safety Solutions (2005)

Para obtener más información sobre las especificaciones técnicas de este equipo ver el Apéndice C.

Normativas de medición

Internacional

ICNIRP

Las directrices dadas por la ICNIRP, i*nternational Commission on Non-Ionizing Radiataion Protection,* fueron adoptadas por varios países para restringir la exposición de los trabajadores (limites ocupacionales) y del público en general (límites poblacionales) a las radiaciones no ionizantes (RNI).

El objetivo de estos estándares es considerar los límites de exposición de campo electromagnéticos (CEM) que pueden prevenir los efectos sobre la salud. Estas mencionan que debajo de los límites dados, la exposición a campos electromagnéticos, es segura de acuerdo al conocimiento científico. Sin embargo, no es un determinante que si se supera dicho límite la exposición sea dañina. Estas normas establecidas por ICNIRP serán consideradas por cada país, para luego establecer una normativa nacional según la coyuntura de Perú.

Las instituciones encargadas en el Perú, adoptaron las recomendaciones ICNIRP 1998 como límites máximos permisibles para el rango de frecuencias de 9 KHz a 300 GHz.

Los límites establecidos por las directrices según las recomendaciones ICNIRP 1998 se seccionaron en dos: límites ocupacionales y límites para el público en general, la cuales se indican en la tabla 6 y tabla 7, estos son observados en el apéndice A.

En el Apéndice A muestra a detalle sobre lo que consta estas normas estables por ICNIRP.

Recomendaciones UIT – TK. 83

La literatura indica:

> La Recomendación UIT-T K.83 facilita indicaciones sobre la manera de efectuar mediciones a largo plazo para el control de campos electromagnéticos (EMF) en zonas seleccionadas de interés público, con el propósito de mostrar que esos campos están bajo control y dentro de los límites previstos. El objetivo de la presente Recomendación es ofrecer al público en general datos claros y de fácil acceso sobre niveles de campo electromagnético expresados en forma de resultados de una medición continua. (UIT, 2011, p.3)

Nacionales

Decreto Supremo N° 010-2005-PCM

Mediante este Decreto Supremo N° 010 - 2005 – PCM, el día 03 de Febrero del 2005, se aprobaron los Estándares de Calidad Ambiental (ECAs) para Radiaciones No Ionizantes indicados en la Tabla 8, está se observa a detalle en el apéndice A.

Este estándar establece los máximos niveles de intensidad de radiaciones no ionizantes que no deben excederse en el medio ambiente, esto con el fin de salvaguardar la integridad de la salud de las personas y del ambiente mismo. (Livia, p.43, 2018).

Capítulo 3

Metodología de desarrollo del proyecto

El diseño del prototipo del medidor de campos eléctricos y magnéticos de baja frecuencia está basado en dos módulos, lo cuales pueden ser visualizado en la Figura 20. El módulo sensor se compone de una tarjeta local de control, una tarjeta analógica y dos sensores isotrópicos para cada tipo de campo. Las señales captadas por ambos sensores serán amplificadas y filtradas en el rango de frecuencia de 0.5 Hz a 32 KHz por la tarjeta analógica, luego estas señales ingresan a un convertidor de corriente alterna (CA) a corriente continua (CC), donde la salida de CC es compatible con el rango de 0-5 V del convertidor de analógico al digital (ADC). Esta misma señal se envía a un comparador para generar una señal digital (0 V o 5 V) compatible con el contador de frecuencia. Los datos obtenidos en la última etapa de la tarjeta analógica serán transmitidos desde la tarjeta local de control hacia el módulo remoto de control por medio de la fibra óptica, en este módulo se visualizará los valores de ambos campos así como el control de activación de los sensores.

En el diseño del sensor de campo magnético se usó bobinas con una misma área transversal, número de vueltas y calibre; asimismo, para el diseño del sensor de campo eléctrico se consideró placas de cobre o aluminio expuesta de forma paralela, de iguales dimensiones y entre ellas un material dieléctrico.

Se usaron los protocolos Toslink y UART para las conexiones y transmisión de datos respectivamente.

Finalmente, el prototipo y el equipo de referencia NARDA EFA 300 ingresan a una etapa de comparación en las mediciones de ambos campos, para el caso de campos magnéticos se usó la bobina Helmholtz y para los campos eléctricos, las placas paralelas de cobre.

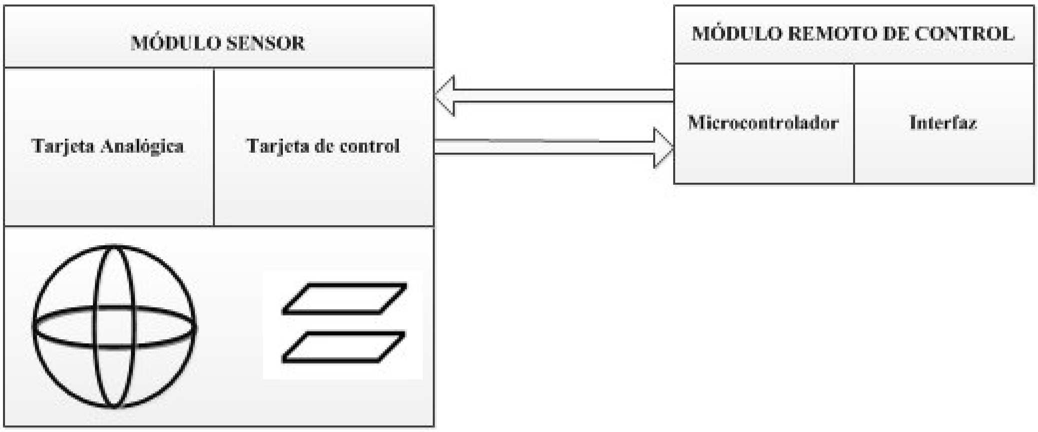

Figura 20. Diagrama de bloques del prototipo de medidor de campos electromagnéticos de baja frecuencia.
Fuente: Elaboración propia.

Principales características del diseño

- El prototipo realiza mediciones de señales en el rango de frecuencia de 0,5 Hz a 32 KHz.
- El sistema trabaja a condiciones normales de temperatura, siendo específicos de modo operacional: -10 ° C a +50 ° C y no operativo (transporte): -30 ° C a +70 ° C.
- Las unidades de los resultados son V/m, A/m, % de estándar (% de estándar está relacionado con la densidad de potencia).
- El rango del display será 0001 a 9999, conmutable entre tríadas variables y permanentes.
- Los tipos de resultados que se muestran en el display son: Último valor actual, máximo, mínimo, promedio.
- Se muestran los últimos valores de cada eje (X, Y, Z).
- El tiempo promedio de medición es de 4 segundos a 30 minutos.
- El estándar de conexión de fibra óptica es Toslink con un largo de fibra óptica de 5 metros.

- ❖ La sonda de campo magnético se dispone de 3 bobinas, cada una de ellas tiene un área transversa 100**π** cm^2.
- ❖ La sonda del campo eléctrico se dispone de 3 placas paralelas, de una dimensión de 6 cm x 6 cm.
- ❖ Las baterías recargables de NiMH estándar, 3300 mAmp/H
- ❖ El Peso de la unidad básico es 350 gramos.

A continuación, se detallará la selección de componentes, los principios físicos del diseño e implementación en cada etapa. El prototipo consta de 2 módulos:

a) Módulo sensor. Consta de una tarjeta local de control, tarjeta analógica y los sensores para el campo magnético y eléctrico

b) Módulo remoto del control. En este se ubica un microcontrolador y una pantalla touch scream para la visualización de datos.

Implementación de la estructura de los módulos

Para el diseño de la estructura que sostiene a los sensores y a las tarjetas electrónicas se utilizó el software de simulación SOLIDWORK, como se aprecia en la figura 21.

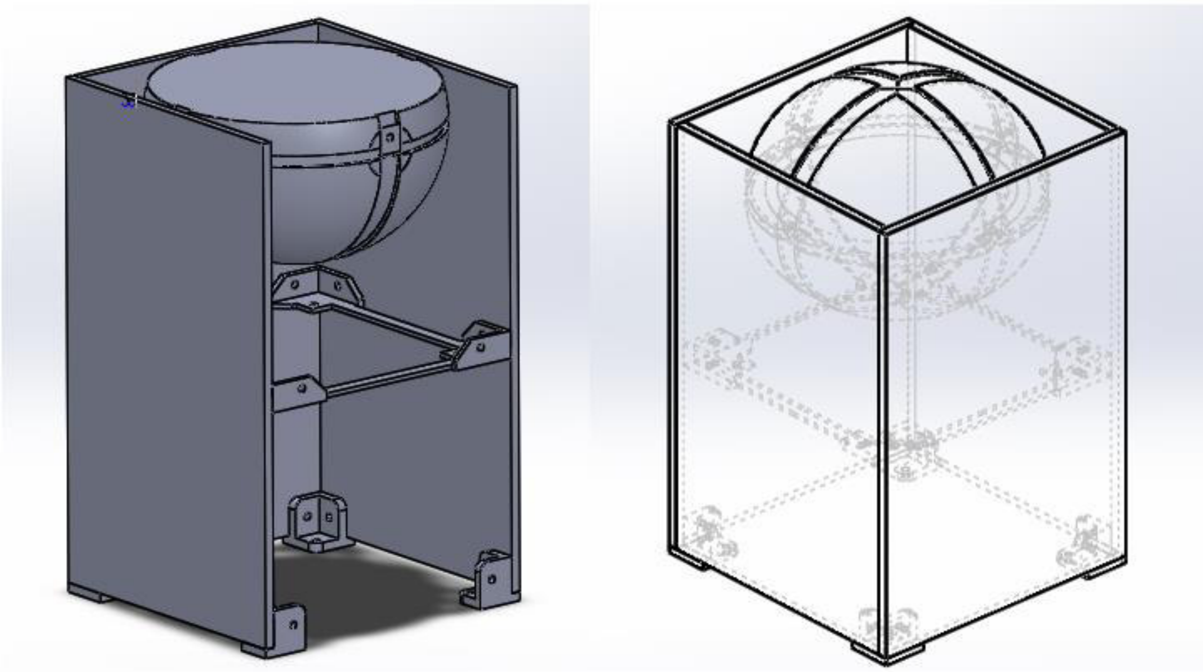

Figura 21. Simulación de la estructura del Módulo Sensor
Fuente: Elaboración propia.

Debido que se trata de un prototipo se procedió a realizar la fabricación de una estructura compacta, para ello se ejecutó cortes uniformes en la plancha acrílica de acuerdo a las medidas obtenidas por el software con el uso de una cortadora laser (Figura 22).

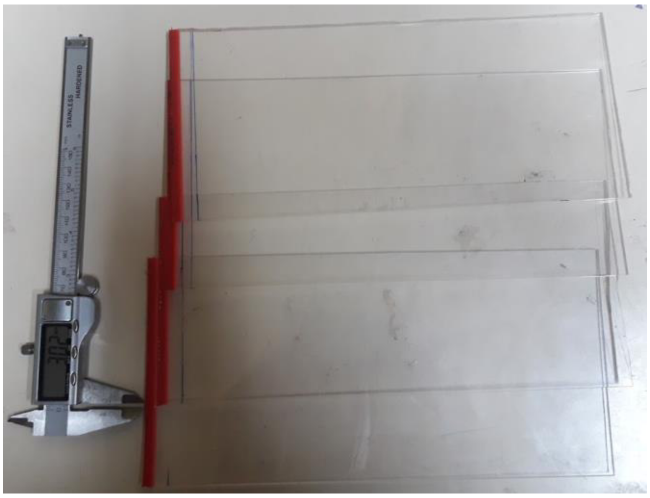

Figura 22. Corte final de la plancha acrílica.
Fuente: Elaboración propia.

Como se mencionó líneas arriba, se requiere una estructura compacta. Por ello se contrató a una empresa especialista en la fabricación de objetos acrílicos en impresoras 3D, la cual se encargó de la elaboración de las piezas que sostendrán los sensores, las tarjetas y a su vez las piezas necesarias para tener una estructura más firme (Figura 23). El diseño final de la estructura se observa en la Figura 24.

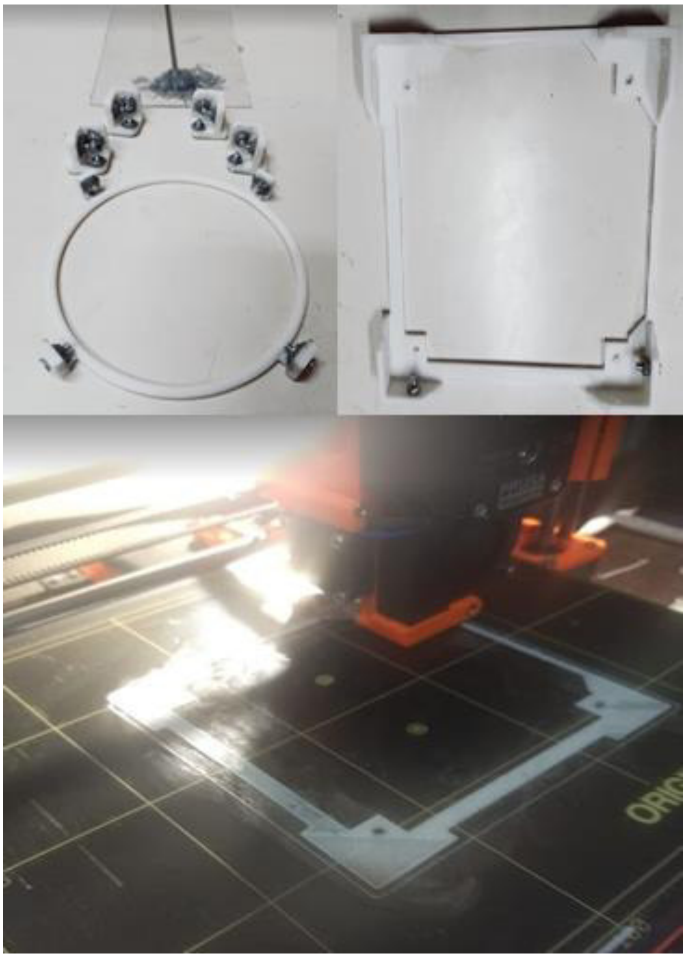

Figura 23. Piezas para la estructura del módulo
Fuente: Elaboración propia.

Figura 24. Módulo Sensor acabado final.
Fuente: Elaboración propia.

Costo de fabricación de la estructura de los módulos

La tabla 4 se presenta los costos de los materiales utilizados en la implementación de la estructura de la caja acrílica y piezas.

Tabla 4

Costo de implementación caja y piezas para el soporte de las tarjetas y sensores

Materiales	**Cantidad**	**Subtotal (S/.)**	**Total (S/.)**
Plancha acrílica 1 m x 1 m	1	270.00	270.00
Transporte de la plancha acrílica para su cortado	1	30.00	30.00
Costo por corte de la plancha acrílica	13	2.50	32.50
Hilera del material para la fabricación de las piezas	1	120	120
Fabricación de piezas	10	5	50
Total		**502.50**	

Diseño e implementación del módulo sensor

Este bloque está constituido por varios sub módulos. Las funciones de esté módulo son: Amplificación, filtrado de señales, transmisión de datos de los valores medidos y la recepción de datos para el control de este. La transmisión y recepción se realiza por medio de la fibra óptica. En la Figura 25 se aprecia la implementación a grandes rasgos.

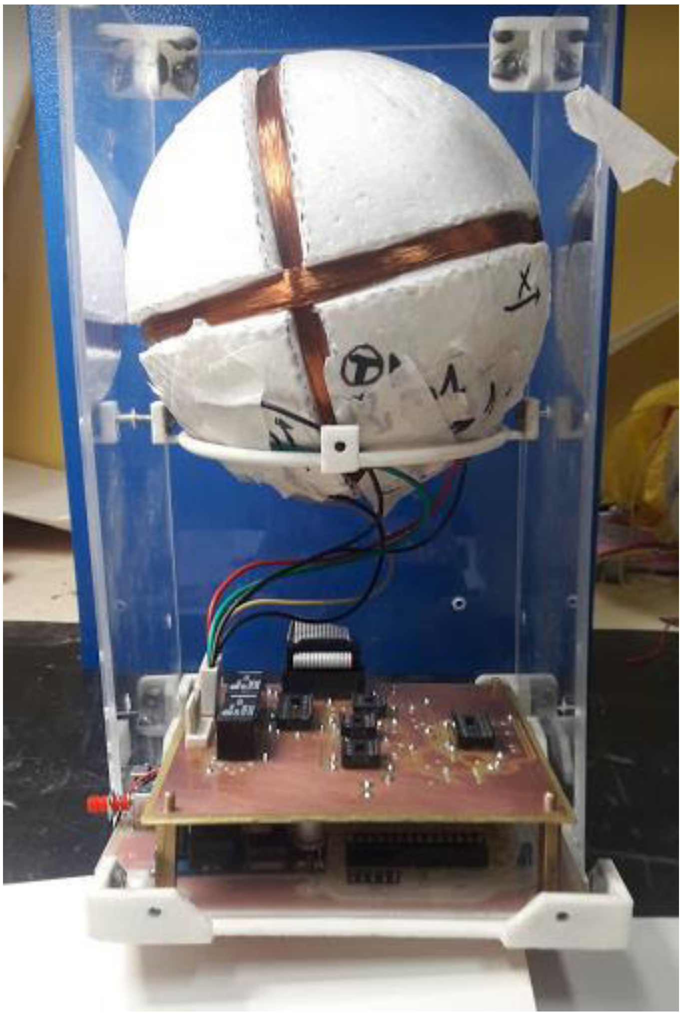

Figura 25. Módulo sensor
Fuente: Elaboración propia.

Sensor del campo magnético

Para el diseño de este sensor se tuvo en cuenta todas las leyes físicas relacionadas a la medición del campo magnético expuesta en el capítulo anterior. De todas ellas se eligió como fundamento la ley de inducción de Faraday que facilita obtener la medición del campo magnético. Según la literatura para esta ley se utiliza una bobina de cobre multivuelta, por ende la forma de la bobina no es significativa.

Elección de la geometría

Para el presente proyecto se consideró tener una bobina circular, básicamente para asemejarnos al equipo de referencia que es el NARDA EFA 300. Este sensor tiene 3 bobina de cobre multivuelta, una para cada eje.

El elemento de bobina es muy adecuado para esta aplicación ya que su sensibilidad es más alta que otros sensores, por ejemplo realizando la comparación con el sensor de efecto hall.

Material

Para la construcción de la bobina, se empleó un cable de cobre, justificado en la baja resistividad eléctrica de cobre, la posibilidad de ser refrigerada, su maleabilidad y bajo costo comercial, en la siguiente tabla menciona las características del sensor.

Tabla 5
Principales especificaciones físicas.

Calibre del cable de cobre	38
Resistencia eléctrica (Ω/1km)	2781.46

Criterios de diseño de la bobina

Según la ley de Faraday la bobina induce una tensión que depende la cantidad de flujo magnético. Esta tensión inducida depende las siguientes variables:

- El coseno del ángulo θ.
- Frecuencia del campo magnético (f).
- Números de giros de la bobina (N).
- El área transversal de la bobina (A).
- El campo magnético (B).

$$V_{in} = N\ 2\pi\ f A\ B\ \cos\theta$$

Como en la implementación el valor de N (número de vueltas) y A (área de transversal de la bobina) son valores constantes, entonces se debe reformar la dependencia del ángulo y la frecuencia para realizar medias isotrópicas y de banda ancha. La disposición ortogonal de las 3 bobinas de medición permite una medición isotrópica del campo, es decir, independiente de la dirección espacial (Molero Castejón, 2013).

Una vez que se tiene el voltaje inducido, se halla la corriente aplicando la ley de ohm.

$$I = \frac{Vin}{R}$$

Donde la resistencia del cable es:

$$R = \frac{longitud\ del\ cable}{\sigma\ Area} = 0{,}386\ \Omega$$

Por lo que resulta la corriente

$$I = \frac{NB_0\ S\ \omega}{R} \sin \omega t$$

Dimensiones

Según el postulado de Faraday, el número de vueltas y área transversal es directamente proporcional al voltaje inducido a dicha bobina, es por ello que se consideró un número de vueltas importante así como el área para obtener un voltaje apreciable para la próxima etapa que es la amplificación.

Luego de considerar estos aspectos, se mandó a fabricar una bobina isotrópica como se muestra en la Figura 26, con las siguientes características:

- Un área transversal(A) = 102.85 cm^2 (r=6.5 cm)
- Número de vueltas (N) = 650
- Se utilizó cobre electrolítico por poseer la característica de alta conductividad
- Metros usados por cada eje 26547 metros.

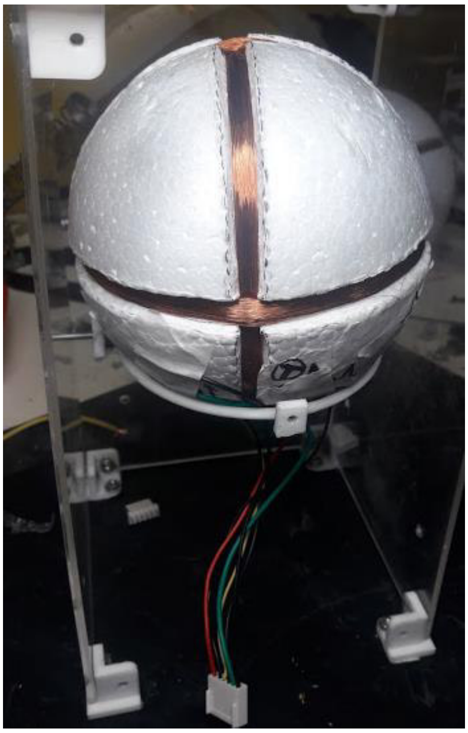

Figura 26. Sensor del campo magnético
Fuente: Elaboración propia.

Las características físicas consideradas fueron con el fin de evitar errores de medidas de campo eléctrico, ya que el sensor está conformado por alambre de cobre que son buenas antenas para captar dicho campo. Ante esto se procedió considerar un área efectiva grande y tener la suficiente sensibilidad aumentando el número de vueltas de cada bobina (Molero Castejón, 2013).

Sensor de campo eléctrico

Para el diseño del sensor de campo eléctrico se consideró viable fabricar un condensador de placas paralelas unidas por el dieléctrico Nylon, de esta forma se mide el potencial eléctrico entre las placas de manera fácil y óptima. Existen otras formas para obtener el valor del campo eléctrico pero por la complejidad se decidió no usarlas. Esta forma de calcular es más sencilla por trabajar con escalares en vez de vectores, como se aprecias en la siguiente formula:

$$V_{AB} = \frac{W}{Q} = -\int_{A}^{B} E.\,dl \qquad \text{V: J/C (volt)}$$

Para la elección de la dimensiones del sensor capacitivo, se consideró 3 tipo de sensores con dimensiones distintas con el fin de obtener un capacitancia considerable, facilidad de diseño y tener una exitosa medición en la siguiente etapa analógica de filtrado y amplificación del campo eléctrico.

Elección de la geometría

Para el presente trabajo se consideró usar un sensor capacitivo de placas paralelas. El sensor capacitivo es adecuado para este tipo de medición por la facilidad de fabricación y sus ventajas en la aplicación.

Material

Para la implementación del sensor capacitivo, se usó placas de cobre, debido a la baja resistividad eléctrica de cobre, conductividad y bajo costo comercial, en la siguiente tabla menciona las características del sensor.

Tabla 6
Especificaciones de la plancha de cobre

Resistencia óhmica máxima	9.38 Ω/100 m a 20°C
Capacitancia	6.6 nF/100 m(Cat. 3) 5.6 nF/100m (Cat. 4 y 5)
Resistencia de aislamiento mínima	1500MΩ - 100 m

Criterios de diseño del sensor capacitivo

Estos sensores tiene el comportamiento similar a los dipolos cortos, debido que las dimensiones de las placas son más pequeñas que la longitud de onda de la señal medida (Molero Castejón, 2013).

La detección del campo se mide la tensión que hay entre las placas de un condensador producida por la corriente de desplazamiento que circula por las placas, generada por el campo eléctrico. Es por ello que calcularemos el potencial eléctrico entre las placas (Molero Castejón, 2013).

Posterior al criterio del diseño del sensor, se consideró la efectividad en captar las señales de baja frecuencia apoyándose de la tarjeta de amplificación haciéndose pruebas con distintas frecuencias.

Dimensiones

El sensor capacitivo ya que tiene un comportamiento similar a un dipolo, se consideró que sus dimensiones deben ser menores a la longitud de onda que se medirá.

A partir del criterio de diseño, se fabricó 3 formas de sensores con distintos tamaño de espesor y geometría, en las siguientes tablas se menciona las dimensiones:

❖ Sensor con dieléctrico cilíndrico

Tabla 7
Dimensiones del sensor con dieléctrico cilíndrico

Dimensiones de la placa del cobre	7 x 7 cm
Espesor de la placa de cobre	0.5 mm
Diámetro del bloque dieléctrico	3.2 cm
Espesor de la placa del dieléctrico	3 cm
Constante dieléctrico del Nylon(K)	3.4

La capacitancia del sensor viene dado por la siguiente fórmula:

$$\mathrm{C} = \frac{\varepsilon \mathrm{A}}{\mathrm{d}}$$

Considerando: ε_o= 8.854 x 10^{-12} F/m

$$\boldsymbol{\varepsilon} = \frac{\boldsymbol{\varepsilon_o}}{\mathbf{k}} = \frac{8.854 \text{ x } 10^{-12}\ \mathrm{F/m}}{3.4} = 2.604\ x\ 10^{-12}\ F/m$$

Por lo tanto:

$$C = \frac{2.604\ x\ 10^{-12}\ \dfrac{F}{m}\ .36\ x\ 10^{-4}\ m^2}{3\ x\ 10^{-2}\ m} = 0.31248\, pF$$

Entonces la capacitancia de acuerdo a las características consideradas, es 0.3124 pF. En la figura 27 y 28 se muestra la implementación de este sensor con las características mencionadas.

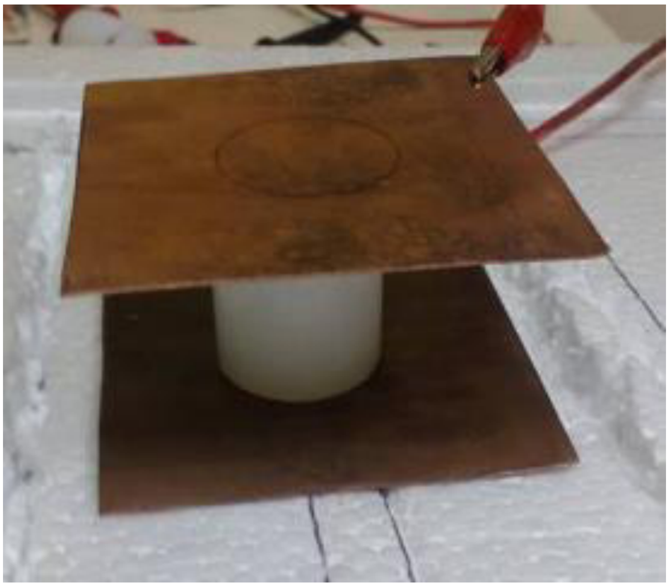

Figura 27. Sensor de campo eléctrico con dieléctrico cilíndrico
Fuente. Elaboración propia.

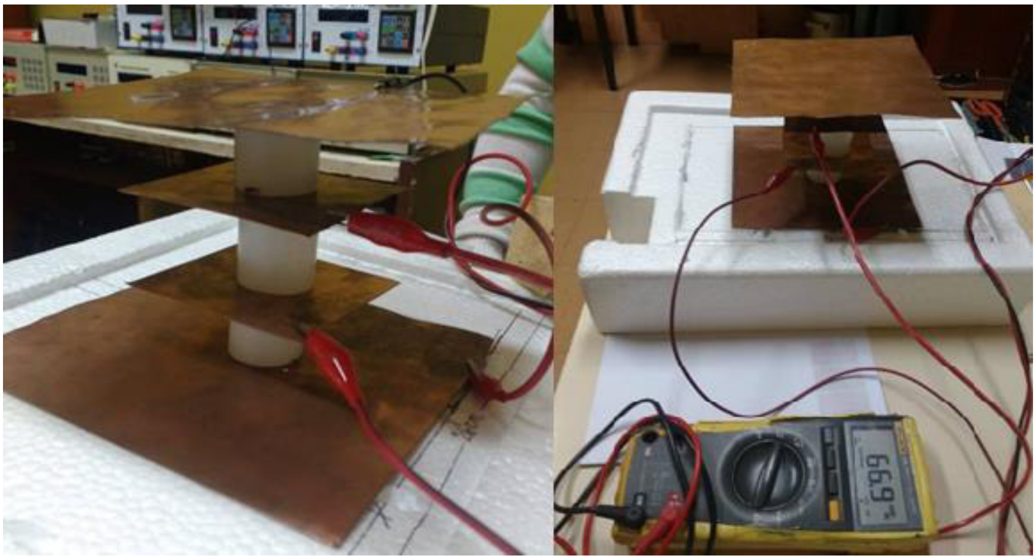

Figura 28. Pruebas del sensor de campo eléctrico.
Fuente. Elaboración propia

- Sensor con dieléctrico cuadrado_1

Tabla 8
Dimensiones del sensor con dieléctrico cuadrado_1

Dimensiones de la placa del cobre	7 x 7 cm
Espesor de la placa de cobre	0.5 mm
Dimensiones del bloque dieléctrico	7 x 7 cm
Espesor de la placa del dieléctrico	12.5 mm
Constante dieléctrico del Nylon(K)	3.4

La capacitancia del sensor viene dado por la siguiente fórmula:

$$\mathrm{C} = \frac{\varepsilon \mathrm{A}}{\mathrm{d}}$$

Considerando: $\varepsilon_o = 8.854 \times 10^{-12}$ F/m

$$\boldsymbol{\varepsilon} = \frac{\boldsymbol{\varepsilon_o}}{\mathbf{k}} = \frac{8.854 \text{ x } 10^{-12} \text{ F/m}}{3.4} = 2.604\ x\ 10^{-12}\ F/m$$

Por lo tanto:

$$C = \frac{2.604\ x\ 10^{-12}\ \frac{F}{m}\ .36\ x\ 10^{-4}\ m^2}{12.5\ x\ 10^{-3}\ m} = 0.749952\ pF$$

Entonces la capacitancia de acuerdo a las características consideradas, es 0.7499 pF, en la Figura 29 y 30 se aprecia el tipo de sensor mencionado.

Figura 29. Fabricación de sensor de campo eléctrico
Fuente: Elaboración propia

Figura 30. Sensor de campo eléctrico con dieléctrico de espesor 12.5 mm
Fuente. Elaboración propia.

- Sensor con dieléctrico cuadrado_2 (Seleccionado para el proyecto)

Tabla 9

Dimensiones del sensor con dieléctrico cuadrado_2

Dimensiones de la placa del cobre	6 x 6 cm
Espesor de la placa de cobre	0.06 mm
Diámetro del bloque dieléctrico	6 x 6 cm
Espesor de la placa del dieléctrico	1.2 mm
Constante dieléctrica del nylon(K)	3.4

La capacitancia del sensor viene dado por la siguiente fórmula:

$$\mathrm{C} = \frac{\varepsilon \mathrm{A}}{\mathrm{d}}$$

Considerando: ε_0= 8.854 x 10^{-12} F/m

$$\boldsymbol{\varepsilon} = \frac{\boldsymbol{\varepsilon_0}}{\mathbf{k}} = \frac{8.854 \text{ x } 10^{-12} \text{ F/m}}{3.4} = 2.604\, x\, 10^{-12}\, F/m$$

Por lo tanto:

$$C = \frac{2.604\, x\, 10^{-12}\, \frac{F}{m}\ .36\, x\, 10^{-4}\, m^2}{1.2\, x\, 10^{-3}\, m} = 7.812\, pF$$

La capacitancia de acuerdo a las características consideradas, es 7.812 pF.

Entonces la unidad del sensor del campo eléctrico, constará de 3 pares de electrodos de placas dispuestos ortogonalmente. Estas serán usadas para medir la corriente dieléctrica causada por la intensidad del campo eléctrico. En la Figura 31y 32 se aprecia la implementación del sensor.

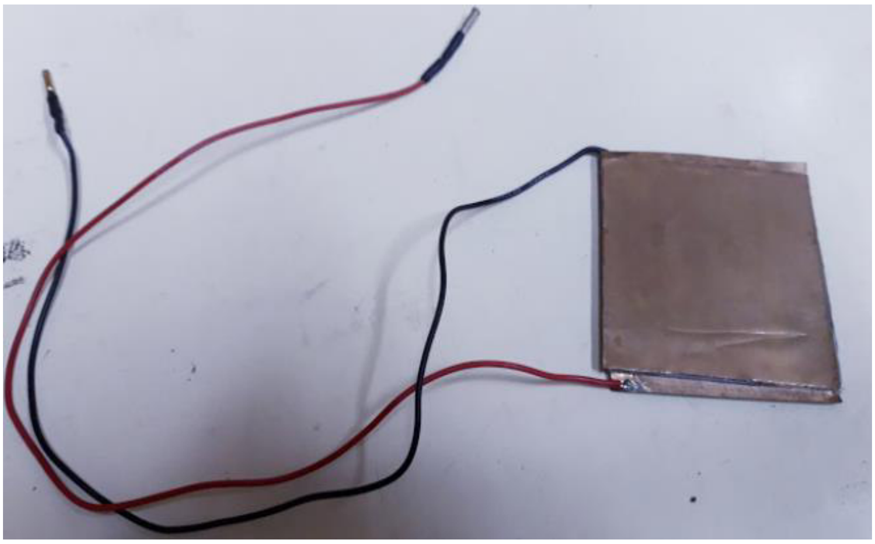

Figura 31. Sensor de campo eléctrico con dieléctrico de espesor 1.2 mm
Fuente. Elaboración propia.

Figura 32. Inicios de la implementación del sensor eléctrico
Fuente. Elaboración propia.

Tarjeta local de control

La tarjeta cuenta con una batería de ion litio para que el módulo sea movible, está batería tiene un voltaje de 3.7 v a 1400 mA/h, la cual es recargable con el módulo TP4056USB. El encargado de encender el módulo es el switch, presionándolo se enciende en su totalidad el módulo de sensor y al apagarlo, la batería realizará la carga mediante el módulo TP4056USB. Esta tarjeta es controlado por el microcontrolador PIC 32MX250F128B, este microcontrolador se conecta con el módulo remoto de control mediante fibra óptica y la comunicación entre ellos es por comunicación serial, para realizar esta comunicación se necesita el estándar de conexión Toslink de transmisión y recepción.

Cada módulo y componente funcionan con 5 v dc, para poder obtener 5 v dc desde los 3.7 v de la batería, se utiliza el módulo conversor DC – DC llamado Step up, con este se eleva el voltaje hasta 7.5 V aproximadamente. Luego de tener un voltaje de 7.5 V, se usara dos reguladores, uno para etapa analógica y otra para la etapa digital como se observa en la figura 32.

La etapa analógica como se observa en la Figura 33 es la tarjeta de amplificación que es alimentado de energía mediante la tarjeta local de control. Se sabe que los amplificadores operaciones requieren voltajes de + 5v y -5v, para eso se usó el integrado MAX860 invirtiendo el voltaje a – 5 v. En la etapa digital que viene a ser la tarjeta en sí, se utiliza un integrado AMS1117 para reducir el voltaje a 3.3 v para ambas fuentes del microcontrolador.

El motivo por el cual no se elevó directamente a 5v desde el conversor DC - DC es para no tener problemas debido al potenciómetro de ajuste del módulo, por ejemplo, ante un movimiento erróneo del potenciómetro el voltaje subiría más de lo permitido por el microcontrolador.

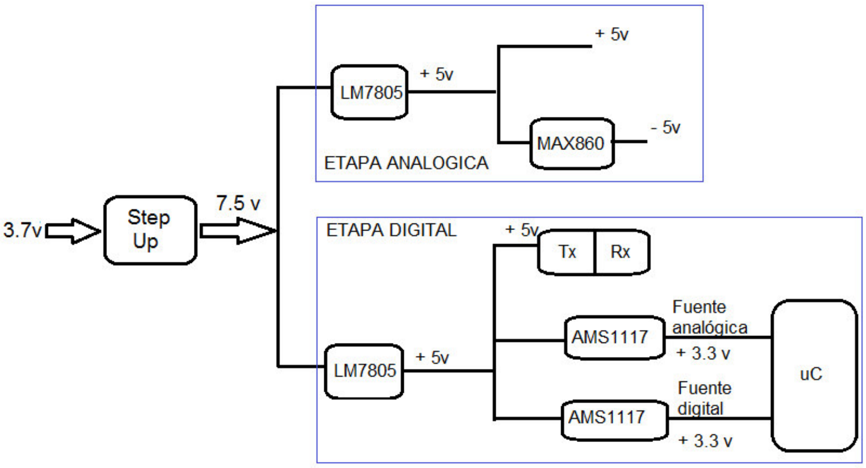

Figura 33. Diagrama de distribución de voltaje
Fuente: Elaboración propia

El intercambio de datos del microcontrolador, los módulos de fibra óptica, y la pantalla nextion se hace mediante el uso del protocolo UART.

Diseño esquemático:

Mediante el software Kicad, se realizó el esquema de la tarje local de control de manera esquemática como se muestra en la Figura 34.

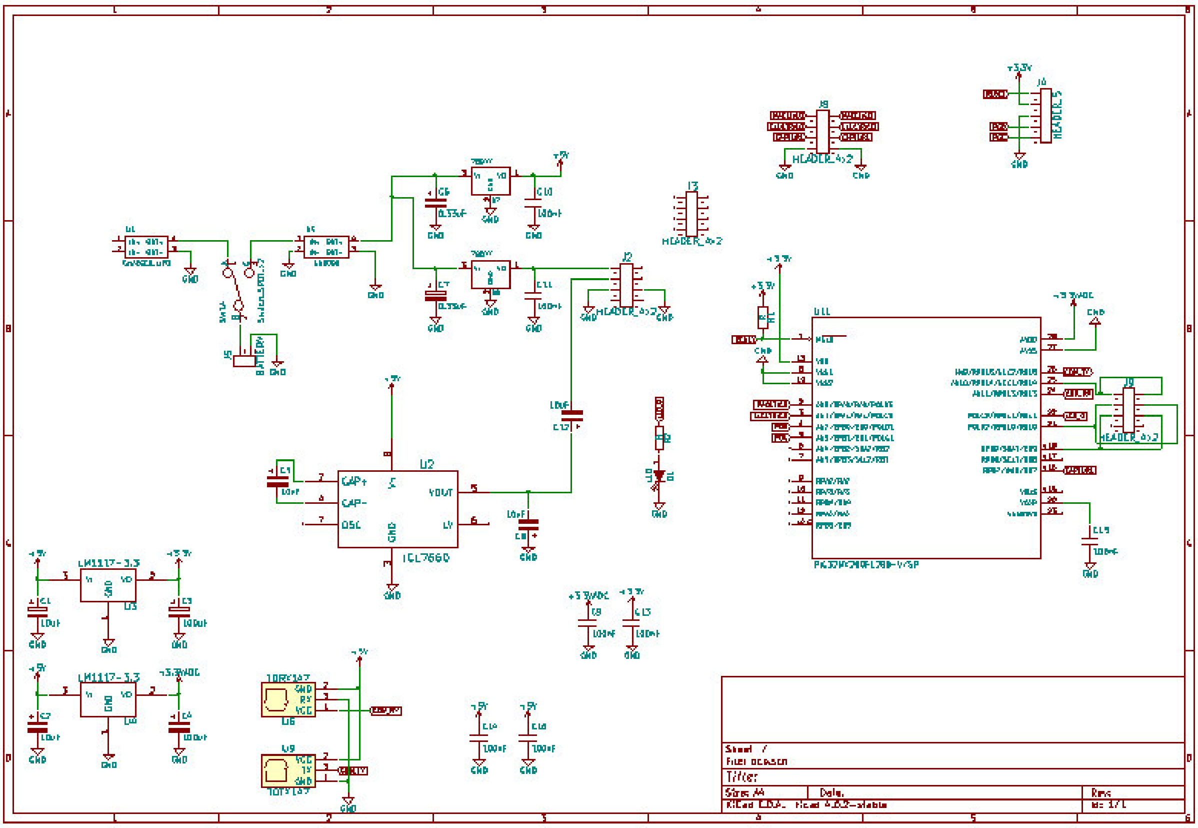

Figura 34. Diseño esquemático de la tarje local de control
Fuente: Elaboración propia.

Diseño PCB:

De la misma forma para el diseño en la tarjeta impresa, se usó el software Kicad. Se aprecia en la Figura 35.

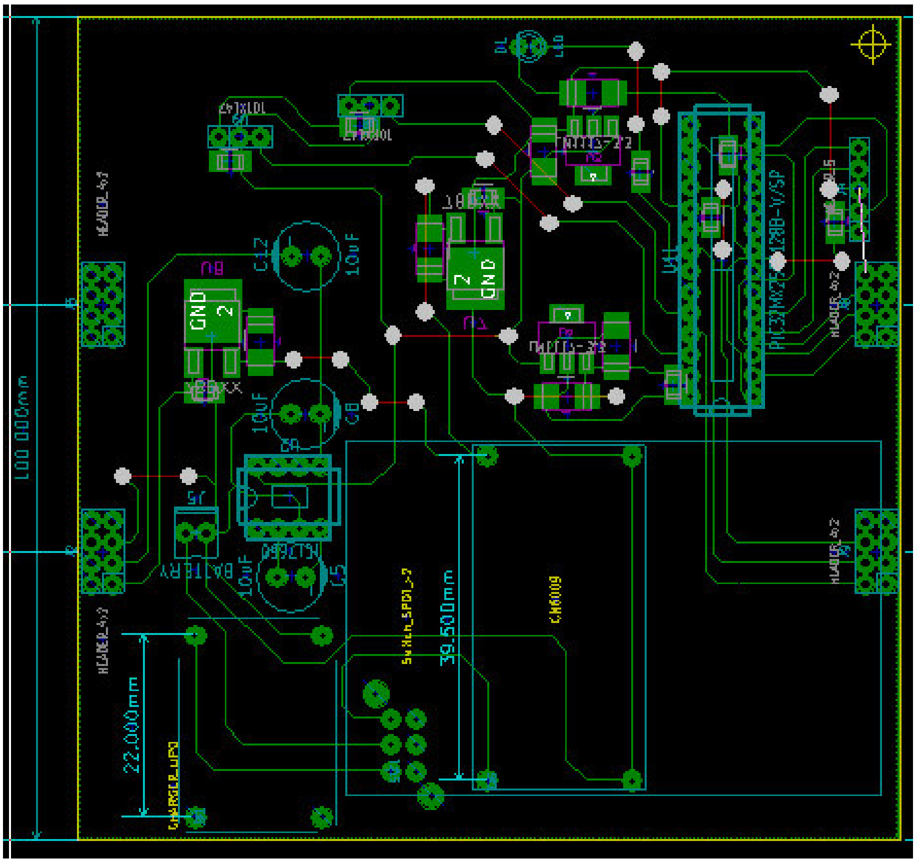

Figura 35. Diseño en PCB de la tarje local de control
Fuente: Elaboración propia

Vista en 3d del diseño

En esta sección se puede visualizar la tarjeta en dimensión 3D como se aprecia en la Figura 36, dándonos una visión más real de cómo quedará la tarjeta al fabricarlo.

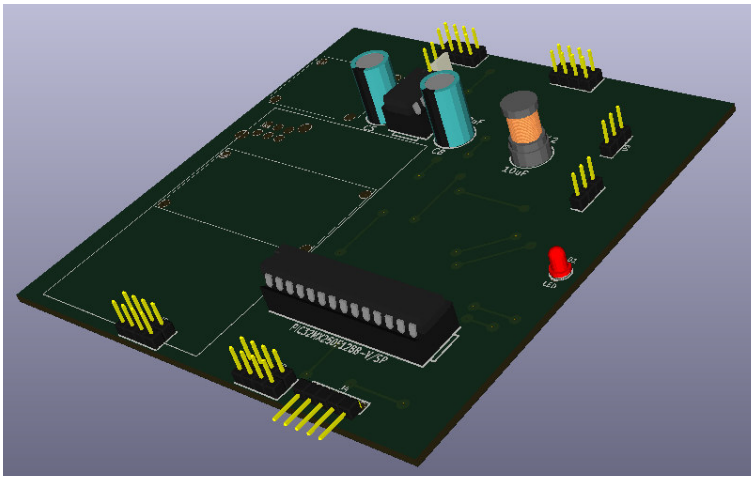

Figura 36. Vista 3D de la tarjeta local de control
Fuente: Elaboración propia

Implementación de la tarje local de control

Se aprecia la fabricación total de la tarjeta local de control con cada sub módulo mencionado en las anteriores secciones. En la Figura 37 se observa cada unidad marcada con distintos recuadros, estos son:

- 1 : Módulo de cargador de baterias.
- 2: Switch.
- 3: Microcontrolador.
- 4: Conexión toslink de transmisión.
- 5: Conexión toslink de recepción.
- 6: Conversor DC – DC.

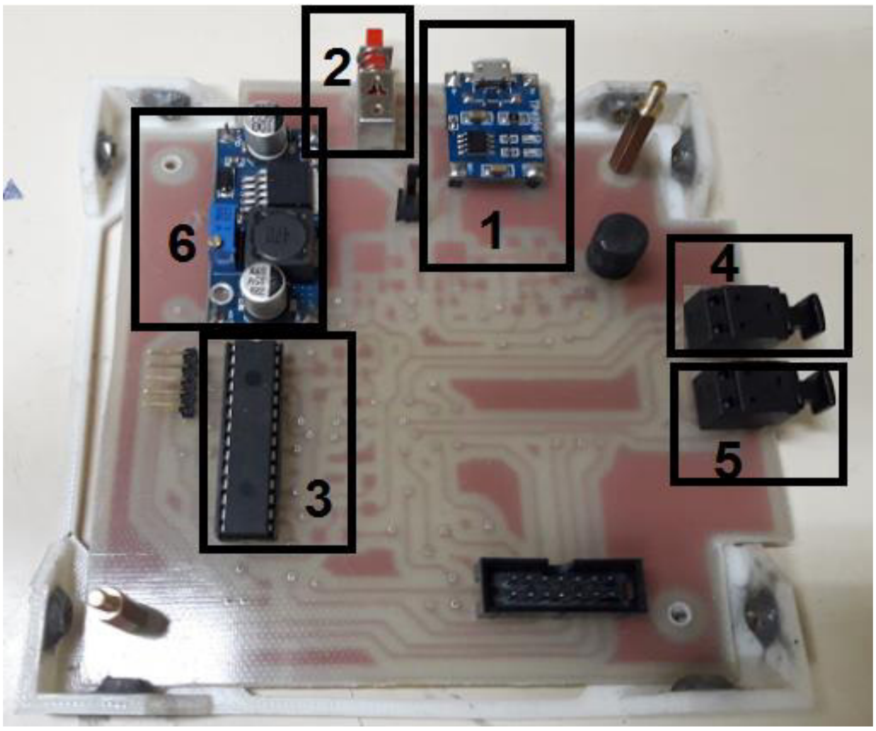

Figura 37. Implementación de la tarjeta local de control
Fuente: Elaboración propia

Tarjeta analógica

Esta tarjeta específicamente tiene la función de seleccionar el tipo de sensor mediante el microcontrolador, amplificar y filtrar las señales captadas, en la Figura 38 se muestra el diagrama de bloques de la tarjeta analógica. Tal como se observa en la Figura 38 se tiene una etapa de selección de sensores, filtros pasa alto y pasa bajo, amplificadores, convertidor AC a DC y un comparador.

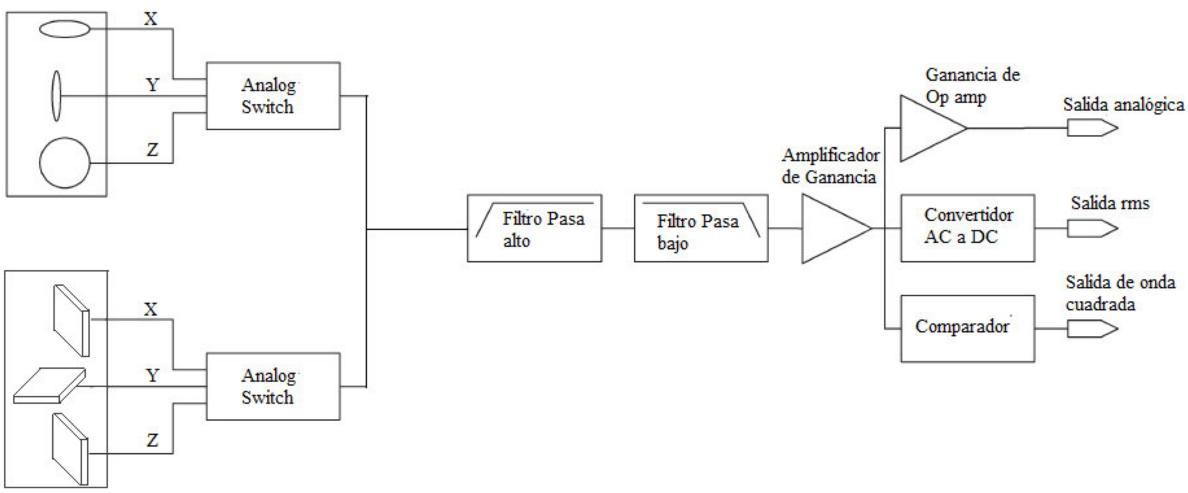

Figura 38. Diagrama de bloques de la tarjeta analógica.
Fuente: Elaboración propia.

Etapa de selección del tipo de sensor.

En el diseño e implementación de esta etapa se usará relés y un multiplexor para realizar la selección del tipo de sensor, sea para campo magnético o campo eléctrico. Se usó un transistor controlado por el microcontrolador para realizar la conmutación de los relés como se muestra en la Figura 39. El microcontrolador emitirá una señal a la base de transistor realizando la conmutación de los relés, de esa forma se obtiene en la salida solo los 3 ejes para un solo tipo de sensor.

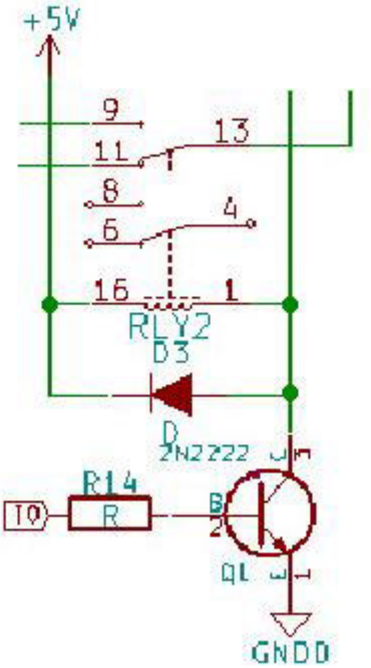

Figura 39. Configuración del transistor controlado por el microprocesador
Fuente: Elaboración propia

Posteriormente se tiene el multiplexor mostrado en la figura 40, esté tiene 8 pines de entradas, 3 pines de activación y una sola señal de salida. El microcontrolador realiza el control de éste para obtener en la salida los valores que se irá midiendo en cada eje, en la tabla 10 se muestra la lógica de activación en el multiplexor.

Tabla 10

Configuración digital del multiplexor

S3	S2	S1	Salida (Z)
0	0	0	Eje X (Yo)
0	0	1	Eje Y (Y1)
0	1	0	Eje Z (Y2)
0	0	0	-
0	0	0	-
0	0	0	-
0	0	0	-
0	0	0	-

Para obtener en la salida solo las señales medidas en las primeras entradas Yo, Y1, Y2 como se muestra en la Figura 40, se estableció la entrada de control a S3=0.

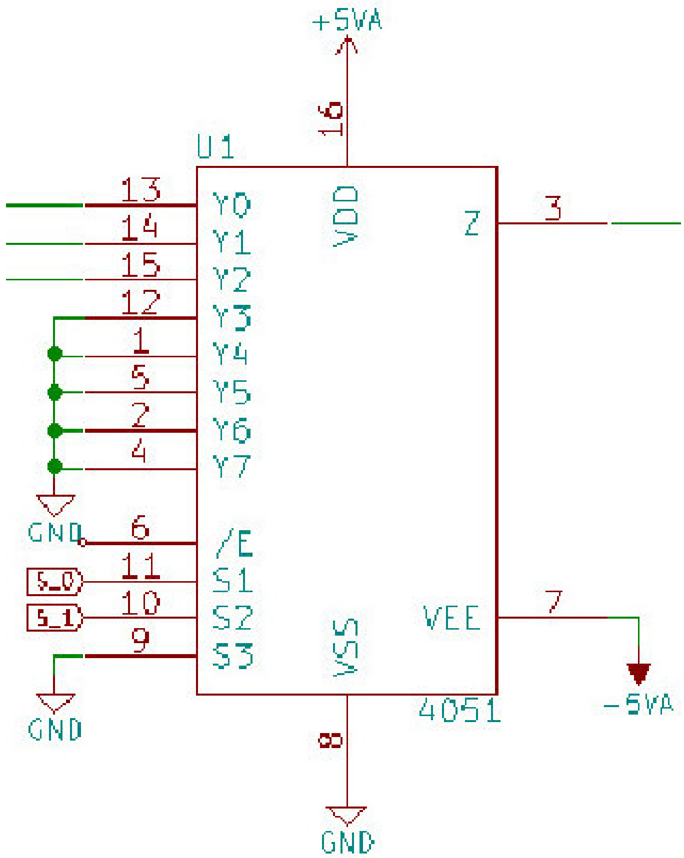

Figura 40. Configuración del multiplexor.
Fuente: Elaboración propia.

Etapa convertidor de corriente a voltaje

El diseño de la tarjeta analógica se considera un convertidor de corriente a voltaje debido que los sensores fabricados de campos magnéticos y eléctricos generan corrientes.

Una ventaja para el diseño del prototipo es tener un voltaje constante independiente de la carga y corriente ingresada.

Para esta configuración se utilizó el integrado TL072, luego se simuló la corriente que serán captadas por los sensores debido a la exposición de los campos magnéticos y eléctricos por una fuente de corriente como se observa en la Figura 41.

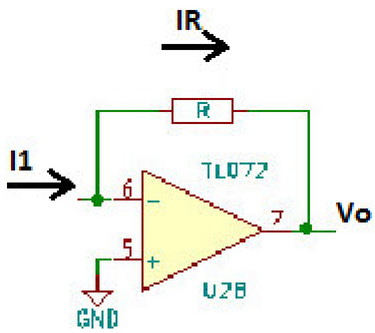

Figura 41. Configuración del convertidor de corriente a voltaje.
Fuente: Elaboración propia.

De acuerdo a la configuración de este amplificador operacional, se tienen las siguientes ecuaciones que ayudan a su comprensión:

$$I1 = IR$$

$$IR = -\frac{V_0}{R}$$

$$I1 = -\frac{V_0}{R}$$

El voltaje de salida es dependiente del valor de la resistencia establecida en el circuito e independiente a la carga en la salida.

Diseño de la etapa de amplificación y filtrado para señales de 0.5 Hz a 32 KHz.

En esta etapa se realizaron pruebas de filtrado de ambos campos por separados, debido que el campo eléctrico es más sensible que el campo magnético, en otras palabras es más dificultoso captar señales de muy bajas frecuencias como 60 Hz. Debido a ello se usaron varias configuraciones de amplificación solo para el campo eléctrico.

Primer intento: Amplificador no inversor

La configuración no inversor se usó para amplificar el voltaje en la caída de tensión en las placas sensores de campo eléctrico, con ganancia de 2, filtro pasa bajo de primer orden a 32Khz y filtro pasa altas a 0.5Hz, para obtener señales a la salida dentro del espectro deseado. (Figura 42).

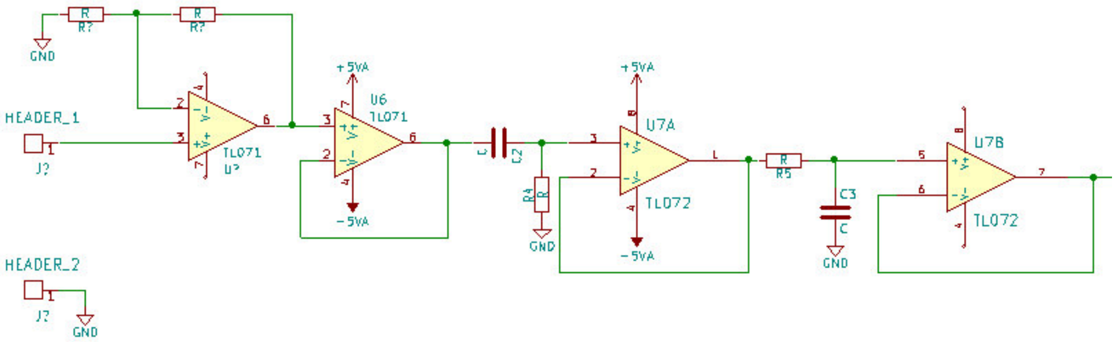

Figura 42. Esquema del amplificador no inversor.
Fuente: Elaboración propia.

La señal capturada a 60Hz no fue muy satisfactoria, puesto que al trabajar con fuentes de alimentación y osciloscopio conectados a la red 220v, su ruido es también detectado con los amplificadores, de esta manera se mezclan junto con la señal deseada. Es por ello que se llega a captar desde los 300Hz hasta los 3Khz.

Segundo intento: Diseño de amplificador, usando un amplificador de instrumentación integrado

Está configuración se supuso que se tendría la señal deseada debido a sus características funcionales que ayudaría en la medición, pero no se pudo obtener un valor apreciable. (Figura 43)

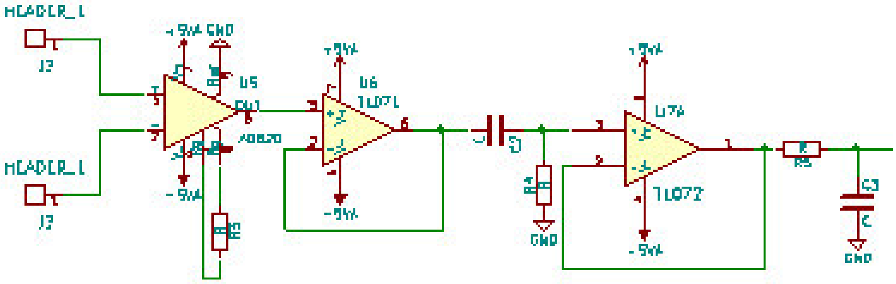

Figura 43. Esquema del amplificador de instrumentación.
Fuente: Elaboración propia.

Tercer intento: Diseño de un amplificador de instrumentación discreto.

El sensor de campo eléctrico es colocado en las entradas del amplificado, en header_1 y header_2.

La amplificación de la señal del generador a 60Hz no es posible de distinguir de la señal de ruido a 60hz que es introducida con el osciloscopio y objetos cercanos que están alterando el circuito. (Figura 44)

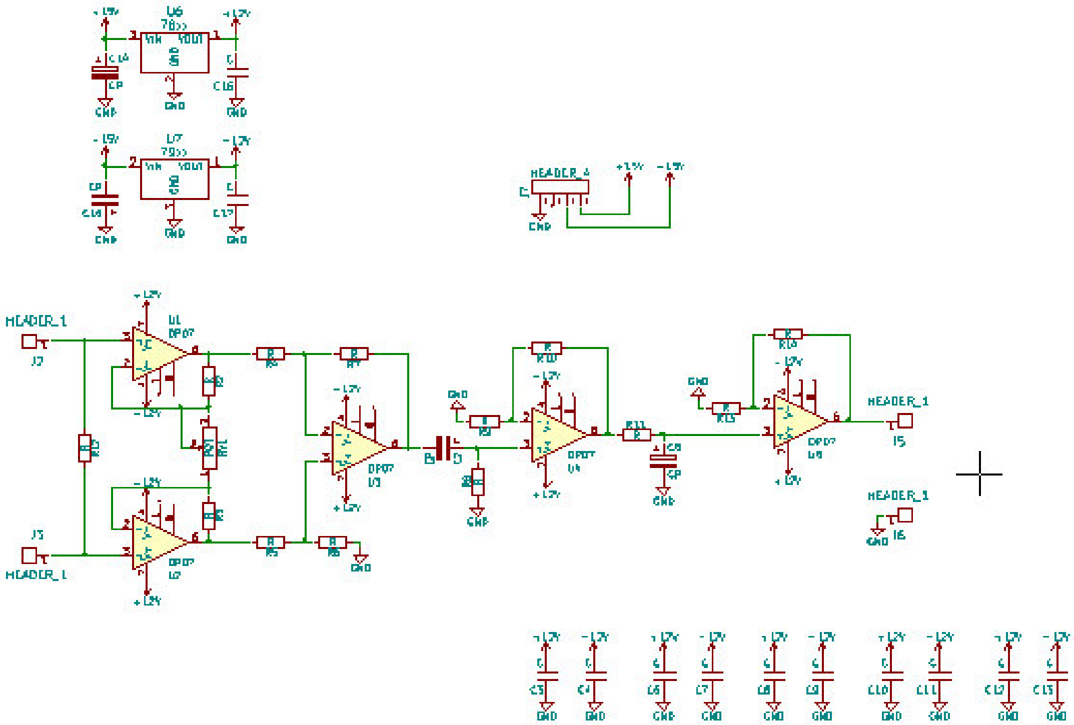

Figura 44. Esquema del amplificador de instrumentación discreta.
Fuente: Elaboración propia.

Cuarto intento:

Después de los intentos expuestos se concluyó lo siguiente: Para el campo magnético se tendrá mediciones en el rango de 0.5 Hz a 32 KHz y para el caso del campo eléctrico solo se realizó mediciones en el rango de 300 Hz a 32 KHz.

Continuando con el diseño de las primeras etapas de la tarjeta analógica, se siguió con el diseño de los filtros pasa alto y pasa bajo.

Diseño de filtro de paso alto y pasa bajo

El diagrama del circuito para el filtro paso alto utilizado en este diseño de detector se muestra en la Figura 45. En las entradas, las señales de alta frecuencia mayores que la frecuencia de corte f0 salen de un filtro de paso alto ideal con amplitud inalterada, mientras las frecuencias menores que la frecuencia de corte f0 están completamente atenuados. Un filtro activo elimina la necesidad de un inductor, que típicamente es el elemento de circuito menos ideal y es voluminoso, pesado y costoso.

Para realizar una medición de alta precisión en un amplio rango de frecuencia, la respuesta de frecuencia de cada etapa de filtro debe ser plana. El uso de valores de componentes estándar y la minimización del recuento de piezas fueron importantes para optimizar el tamaño de la placa y reducir el costo de producción.

Para el presente proyecto se escogió el filtro de paso alto cuadrático Sallen-Key. Este tipo de filtro activo permite que la frecuencia de corte (f0) y el factor de amortiguación (Q) se sintonicen fácilmente utilizando valores de componentes estándar. Mantener Q cerca de uno reducirá los efectos de las variaciones de los componentes sobre el factor de amortiguación, lo que minimizará los sobreimpulsos y subimpulsos. La función de transferencia de esta configuración del filtro es:

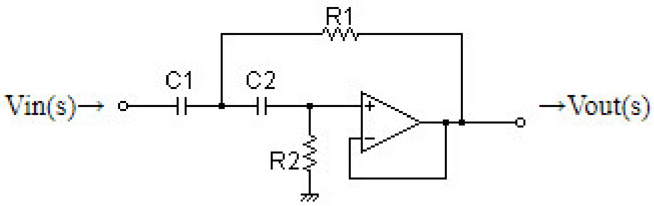

Figura 45. Circuito del filtro pasa alto
Fuente: Elaboración propia

Cut-off frequency:

$$fc = \frac{1}{2\pi\sqrt{R1C1R2C2}}$$

Transfer function:

$$\frac{Vout(s)}{Vin(s)} = \frac{s^2}{s^2 + 2\zeta(2\pi f_c)s + (2\pi f_c)^2}$$

$$Q = \frac{1}{2\zeta}$$

Donde K se conoce como ganancia de alta frecuencia, y Q es un factor de amortiguación; puede oscilar entre 0.5 y 100, con valores típicos cercanos a la unidad.

La ganancia se establece en función del requisito del sistema de tener una señal 0-5-V que impulse el ADC. El factor de amortiguación se seleccionó para minimizar el sobreimpulso y el subimpulso de la respuesta del filtro de paso alto. Los resultados de simulación para los filtros de paso alto de segundo orden, primer orden e ideal se muestran en la Figura 46 con una magnitud en decibelios frente a la frecuencia. Tenga en cuenta que la pendiente asintótica de baja frecuencia es 40 dB / dec para el filtro de segundo orden y 20 dB / dec para el filtro de primer orden. La caída más brusca del filtro de segundo orden está más cerca de la respuesta ideal, y esto produce una respuesta más lineal cerca de la frecuencia de corte.

Los valores de los componentes elegidos en este diseño son los siguientes:

C1 = 47 nF, C2= 47 nF, R1= 6.8 MΩ, R2 = 6.8 MΩ, Q= 0.707.

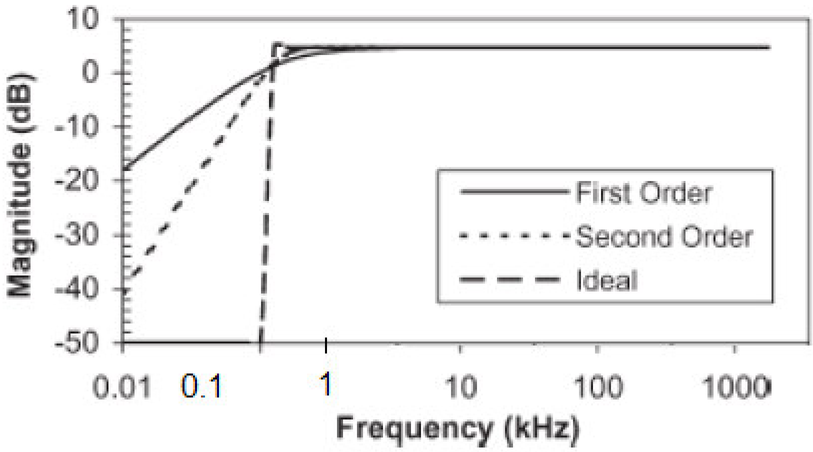

Figura 46. Respuesta de frecuencia de filtro pasa alto de primer y segundo orden.
Fuente: Elaboración propia.

El diagrama de circuito para el filtro activo de paso bajo se muestra en la Figura 47. Un filtro de paso bajo ideal se caracteriza por la frecuencia de corte f0, que indica que las entradas sinusoidales con una frecuencia menor que f0 atraviesa el filtro con amplitud inalterada, mientras que aquellos con una frecuencia mayor que f0 están completamente atenuados.

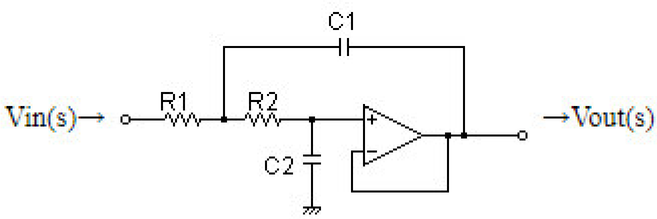

Figura 47. Circuito del filtro pasa bajo
Fuente: Elaboración propia.

Los requisitos de diseño para el filtro de paso bajo son similares a los del filtro de paso alto. Un circuito de filtro activo de paso bajo con ganancia de CC cumple con todos los objetivos de rendimiento y costo.

Por las mismas razones que ya se han discutido en la sección de filtro de paso alto.El diseño requiere que se identifiquen valores de componentes adecuados para obtener los valores deseados de f0, ganancia y Q. Este diseño requiere f0 = 32 kHz, y Q = 1/ √2.Los valores de los componentes elegidos en este diseño son los siguientes: C1 = 47 nF, C2= 47 nF, R1= 110 Ω, R2 = 110 Ω, Q= 0.707.

Los resultados de la simulación para los filtros de paso bajo de segundo orden, primer orden e ideal se muestran en la Figura 48, con una magnitud en decibelios frente a la frecuencia. Se tiene en cuenta que la pendiente asintótica de alta frecuencia es de 40 dB / dec para el filtro de segundo orden.

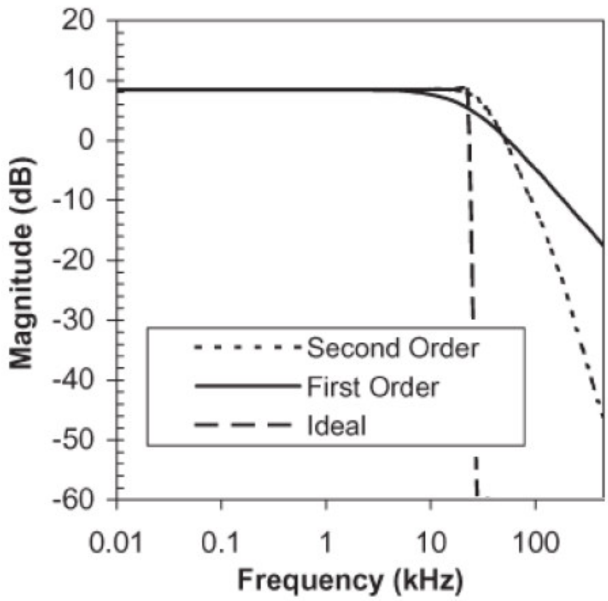

Figura 48. Respuesta de frecuencia de filtro pasa bajo de primer y segundo orden.
Fuente: Elaboración propia.

Los circuitos en las Figs. 45 y 47 están conectados entre sí, produciendo un filtro pasabanda ancho de segundo orden con linealidad máxima, que se muestra en la Figura 49. Esta figura también incluye las respuestas de filtro ideales de primer orden para comparación.

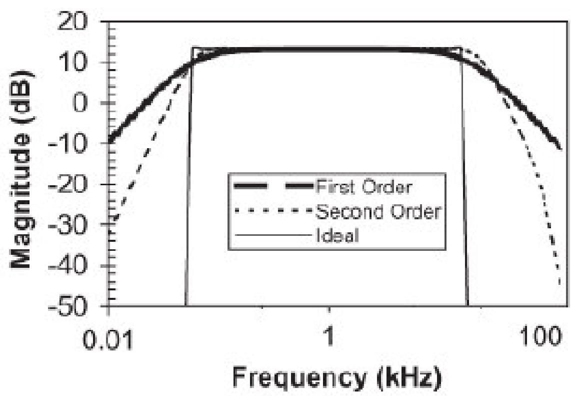

Figura 49. Respuesta de frecuencia de filtro pasa bajo y pasa alto de primer y segundo orden.
Fuente: Elaboración propia.

Diseño del convertidor de CA a CC

Al final, se requiere una entrada de señal de CC sin fluctuaciones como la entrada a la parte digital del diseño de este sistema; por lo tanto, la señal amplificada (ac) se alimenta a través de un convertidor de CA a CC. El circuito de precisión de CA a CC utilizado en este proyecto se muestra en la Figura 50. Su función con el condensador C2 eliminado del circuito se explica de la siguiente manera. Para las señales de entrada negativas, el primer amplificador operacional (op-amp) OA3 es cero, y ninguna corriente fluye a través de R3. La salida del segundo op-amp OA4 es:

$$E_{out} = -\frac{R7}{R6} E_{in}$$

Para señales de entrada positivas

$$E_{out} = R7 \left[\frac{E_{in}}{R3} - \frac{E_{in}}{R6}\right]$$

Si R3 = (1/2) R6, la salida es (R7 / R6) Ein; por lo tanto, la salida es siempre el valor absoluto de la entrada.

Al agregar el condensador C1 a través de R7, el op-amp OA4 produce una salida promedio pura de CC.

La constante de tiempo del filtro R7C2 tiene que ser mayor que el período máximo de la señal de entrada para tener un buen filtrado o promediado sin ninguna ondulación. En nuestro caso, la frecuencia de entrada mínima de la señal es de 0.5 Hz; entonces, T = 0.5 s, y la constante de tiempo R7C2 >> 0.5 s es necesaria.

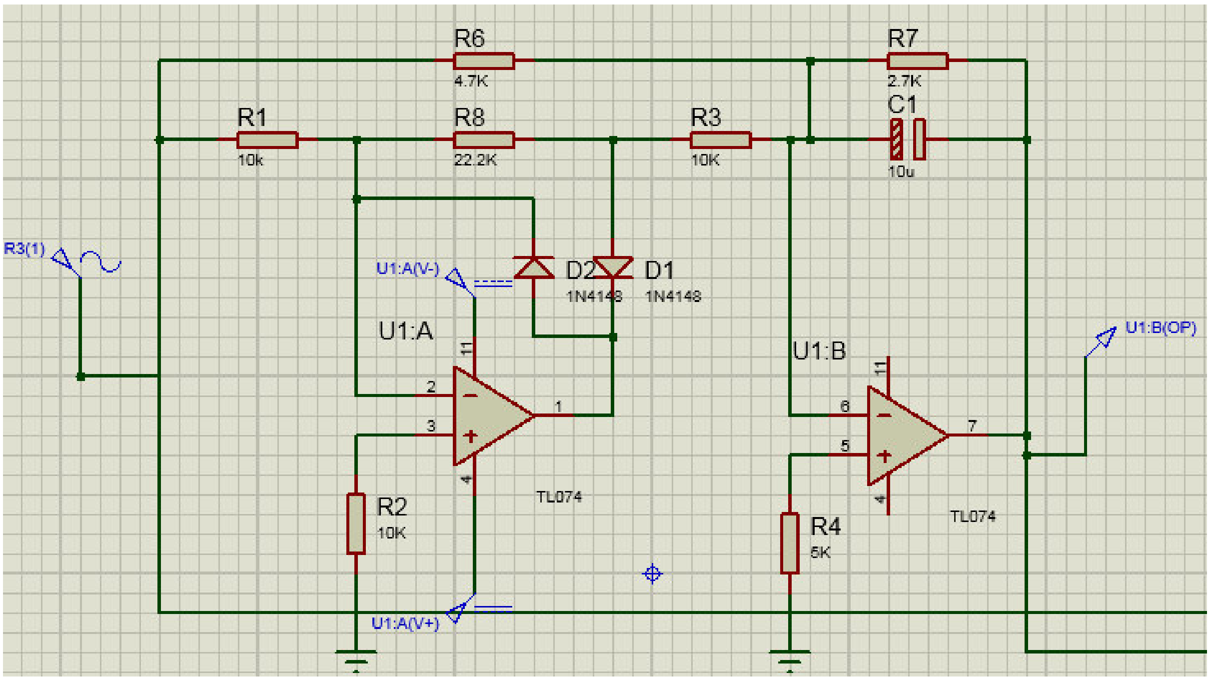

Figura 50. Convertidor AC a DC.
Fuente: Elaboración propia

La salida de CC se puede ajustar para que corresponda con el RMS o el pico de la entrada de CA. Para una entrada sinusoidal Ein = vi sin ωt, la salida promedio de CC está dada por

$$E_{out} = \frac{0.64\ v_i R7}{R6}$$

Los valores de los componentes para el circuito mostrado en la Fig. 50 son R1 = 10 kΩ, R2 =10 kΩ, R3 = 10 kΩ, R4 = 5 kΩ, R6 = 4.7 kΩ, R7 = 2.7 kΩ, R8 = 22.2 kΩ y C1 = 10 µF.

Durante la construcción, los cables deben mantenerse cortos, los valores de resistencia del tipo de película deben mantenerse bajos, las fuentes de alimentación deben pasarse por alto con condensadores de disco de cerámica de 10 µF, los diodos D1 y D2 deben ser razonablemente rápidos y los amplificadores deben tener bajas corrientes de polarización Seguir estas pautas reducirá las resistencias y capacitancias parásitas, limitará el ruido en el sistema y mantendrá los circuitos no lineales en una región de operación lineal. Cuando se combinan estos pasos dan como resultado una operación que se acerca más a lo ideal y permite que los componentes en la placa funcionen a altas frecuencias con una degradación mínima del rendimiento.

El resultado de la salida simulada para una señal de entrada de onda sinusoidal de 5 kHz con una amplitud de 50 mV se muestra en la Figura 51. Esta prueba muestra la importancia de agregar C2 a través de R7 para actuar como una red activa de filtro de paso bajo. Este filtro elimina las fluctuaciones en el voltaje rectificado e idealmente proporciona un voltaje constante de CC de valor constante para la entrada al ADC.

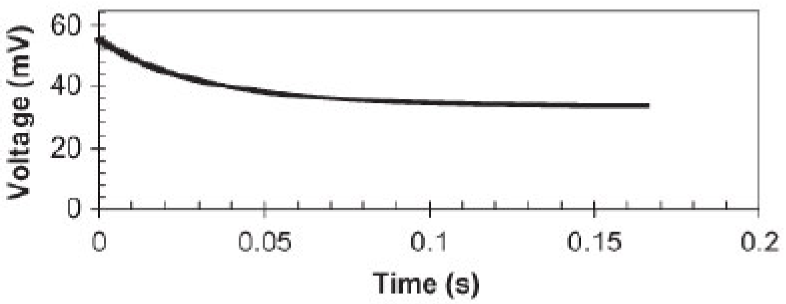

Figura 51. Respuesta de la señal del convertidor de CA a CC RMS.
Fuente: Elaboración Propia

Comparador con diseño de histéresis

Una de las características del diseño del circuito es el indicador de frecuencia. Por lo tanto, el microcontrolador PIC32MX250F128B se utiliza para contar el número de pulsos digitales (0 V o 5 V) por segundo. El esquema del diseño del circuito utilizando el comparador LM311 se muestra en la Figura 52. Los valores de los componentes para el circuito comparador son R43 = R53 = R54 = 10 KΩ y R51 = 1 MΩ. El comparador compara las dos señales de voltaje en su entrada y determina cuál de las dos señales es más grande. Esta función es extremadamente útil para detectar los límites de alta y baja tensión para el contador de frecuencia. Dado que la salida LM311 tiene forma de transistor n-p-n de colector abierto, se utiliza una resistencia de tracción externa R43 para impulsar una carga de salida con una tensión de alimentación (5 V) que es diferente del circuito comparador. Esta característica hace que LM311 sea muy adecuado para su uso con el Pic32mx250f128B.

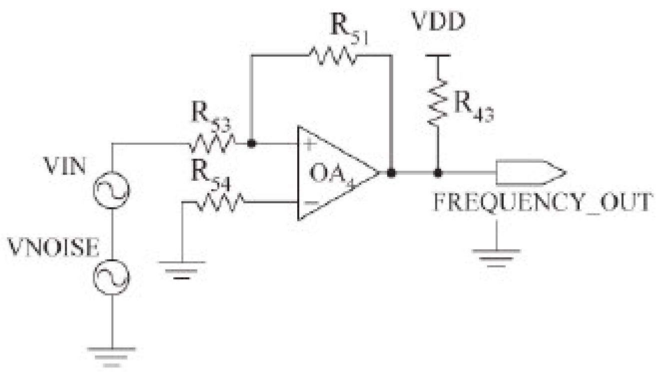

Figura 52. Comparador con diseño de circuito de histéresis.
Fuente: Elaboración propia.

El diseño esquemático de la tarjeta de analógica (Figura 53).

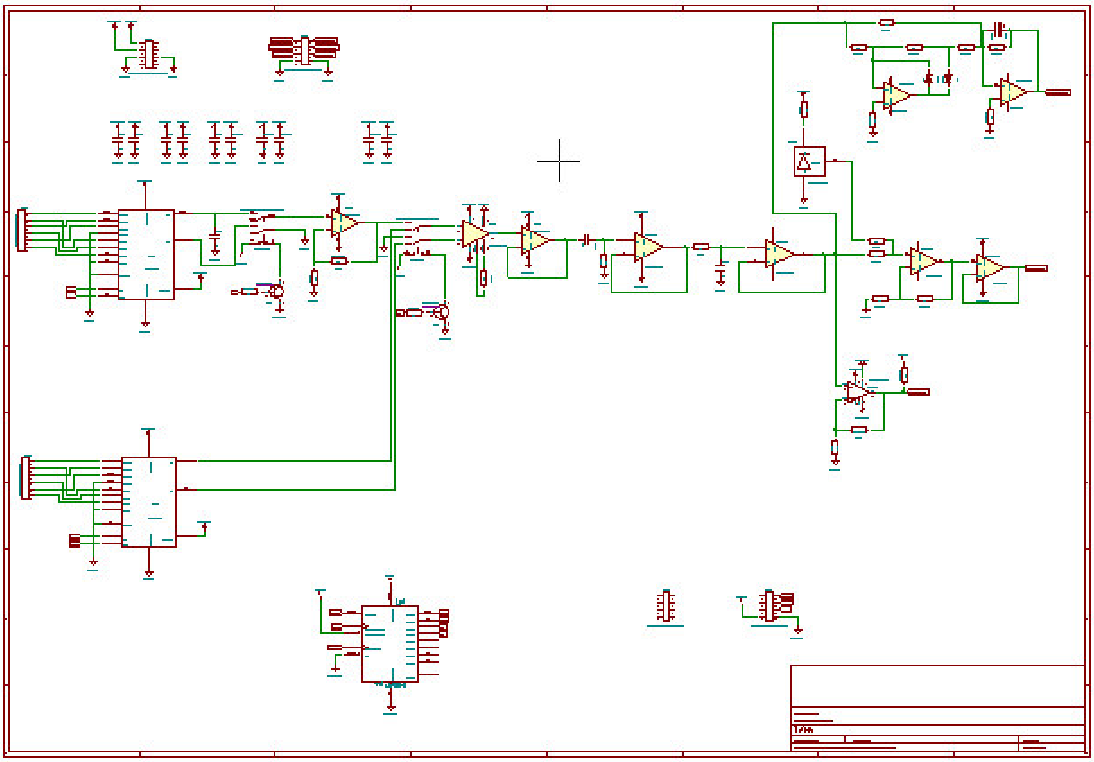

Figura 53. Diseño de la tarjeta analógica.
Fuente: Elaboración propia.

En el software Kicad se diseñó la tarjeta analógica en PCB (Figura 54).

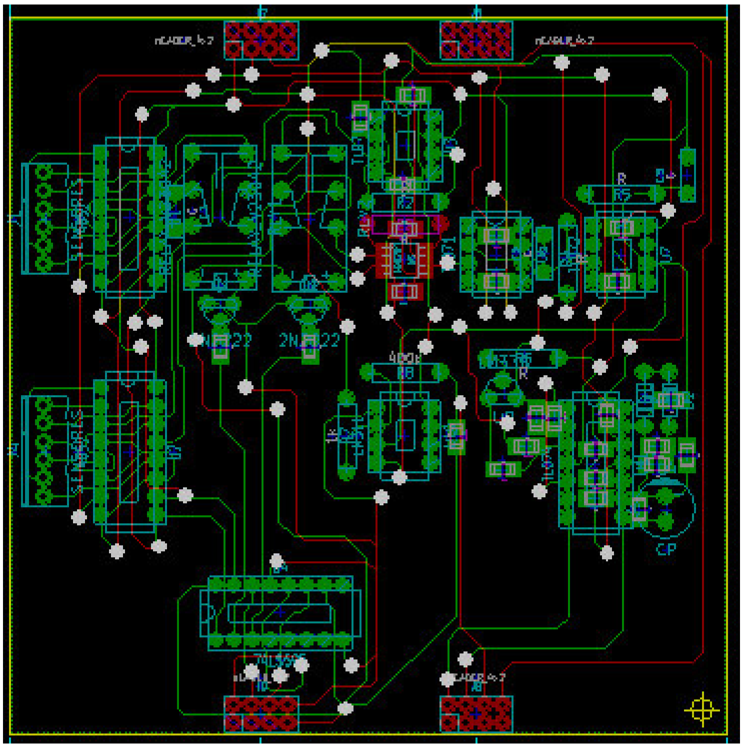

Figura 54. Diseño PCB de la tarjeta analógica.
Fuente: Elaboración propia.

En el software Kicad se tiene una vista en 3D (Figura 55).

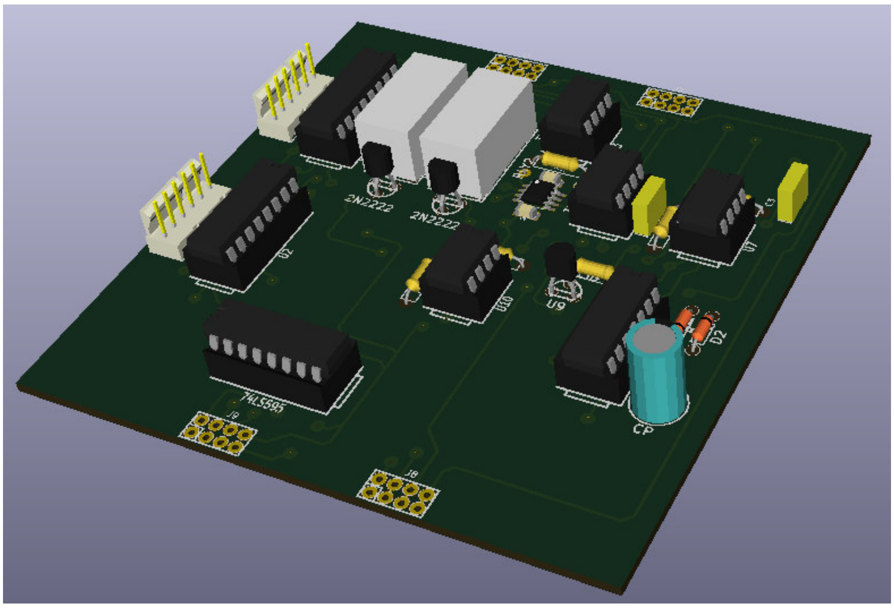

Figura 55 Vista 3D de la tarjeta analógica.
Fuente: Elaboración propia.

La implementación de la tarjeta analógica se observa en la Figura 56.

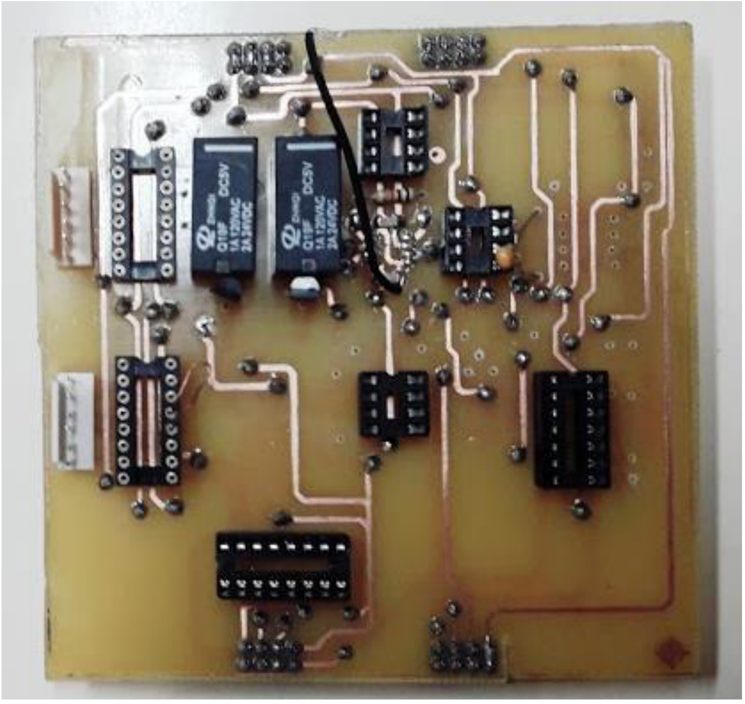

Figura 56. Tarjeta analógica.
Fuente: Elaboración propia.

Costo de fabricación del módulo sensor

La tabla 11 presenta los costos de los materiales utilizados en la implementación de la estructura de la caja acrílica y piezas.

Tabla 11

Costo de implementación del módulo sensor

Materiales	Cantidad	Subtotal (S/.)	Total (S/.)
Cable de cobre electrolítico #38	1	15.00	15.00
Fabricación del sensor de campo magnético	1	60.00	60.00
Plancha de cobre 1m x 1m (espesor 0.5 mm)	1	85.00	80.00
Plancha de cobre 1m x 1m (espesor 0.06 mm)	1	30.00	30.00
Componentes electrónicos pasivos (resistencias, condensadores)	30	0.1	3
Relés	3	5.00	15.00
Microcontrolador	1	60.00	60.00
Conectores Ópticos TOSLINK	3	10.00	40.00
Integrado MN4051B	3	8.00	24.00
Integrado TL072	3	3.00	9.00
Integrado AD627	3	15.00	45.00
Integrado LM311	3	60.00	60.00
Integrado TL074	3	2.00	6.00
Reguladores de voltaje	1	4.00	4.00
Módulo fijador de voltaje	1	10.00	10.00
Módulo cargador de batería	1	12.00	12.00
Batería Ion litio 3.7 v 3300 mAmp/H	1	15.00	15.00
Placas de cobre para las tarjetas electrónicas (1 metro x 1 metro)	1	30.00	30.00
Total		502.50	

Diseño e implementación del módulo remoto de control

El aparato para que sea transportable cuenta con una batería de ion litio de 3.7 v a 1400 mA/h la cual es cargable con el módulo TP4056USB. El switch es encargado de encender y apagar el equipo, mientras este se encuentra presionado se encenderá el equipo y al momento de liberarlo lo apagará y estará listo para la carga de la batería mediante el módulo de carga (1).

El equipo es controlado mediante el microcontrolador PIC 18f46k22 que funciona a 5v, y la comunicación serial con el sensor se hace mediante el uso de fibra óptica con los módulos de conexión Toslink de transmisión y recepción. Estos módulos y el microcontrolador funcionan con 5 Vdc, entonces para poder obtener 5 Vdc desde los 3.7 v de la batería, se utiliza el modulo conversor DC – DC Step Up basado en el integrado XL6009, con el cual se eleva el voltaje de la batería hasta 7.5v aproximadamente, luego reducimos el voltaje hasta 5 Vdc estable con el regulador fijo LM 7805. El motivo de no elevar el voltaje directamente a 5 v desde el conversor DC/DC es para no tener problemas debido al potenciómetro de ajuste del módulo, un movimiento erróneo del potenciómetro y el voltaje subiría hasta más de lo permitido por el microcontrolador.

Posteriormente al obtener el voltaje requerido, el microntrolador da órdenes al módulo sensor mediante enlace de fibra óptica, este módulo estará listo para recibir los datos que el sensor envía, luego en la pantalla LCD se observa los valores de las mediciones captadas por los sensores, esta pantalla LCD se encuentra conectado a microcontrolador mediante el conector molex de 4 pines (Figura 57).

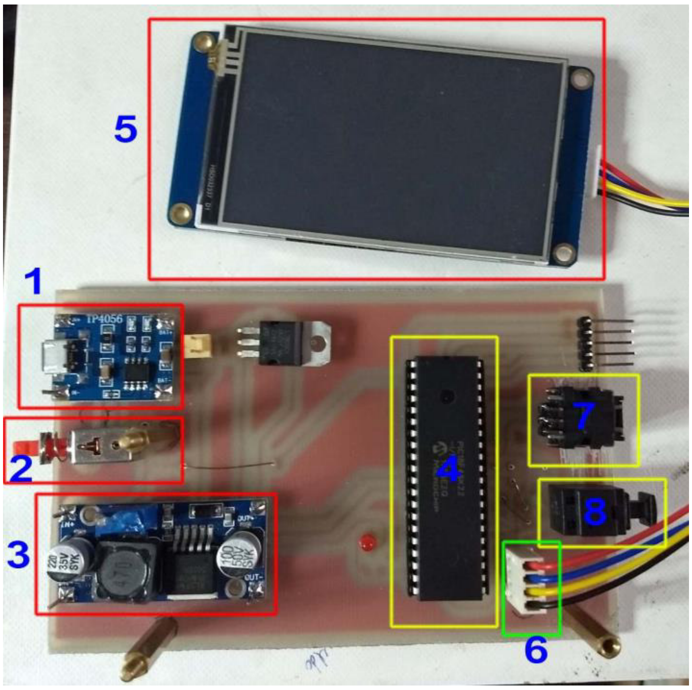

Figura 57 Implementación de la tarjeta de control.
Fuente: Elaboración propia.

Se usó el protocolo UART para el intercambio de datos del microcontrolador, los módulos de conexión TOSLINK de fibra óptica y para la pantalla nextion, debido a esto el microntrolador requiere dos módulos UART para comunicarse con ellos, es por ello la elección del microcontrolador PIC 18f46k22 que cuenta con dos módulos integrados de comunicación UART.

En el módulo de carga TP4056 se ha modificado la resistencia Rprog a 3.9 kΩ para realizar la carga con una corriente de 410 mA con el objetivo de prolongar la vida útil de la batería. En la tabla 12 se observa con más detalle las diferentes proporciones para obtener distintos valores de corriente de carga.

Tabla 12
Rprog Current Setting

Rprog (K)	Ibat (mA)
10	130
5	250
4	300
3	400
2	580
1.66	690
1.5	780
1.33	900
1.2	1000

En la figura 58 se observa a detalle el diseño esquemático del módulo remoto de control.

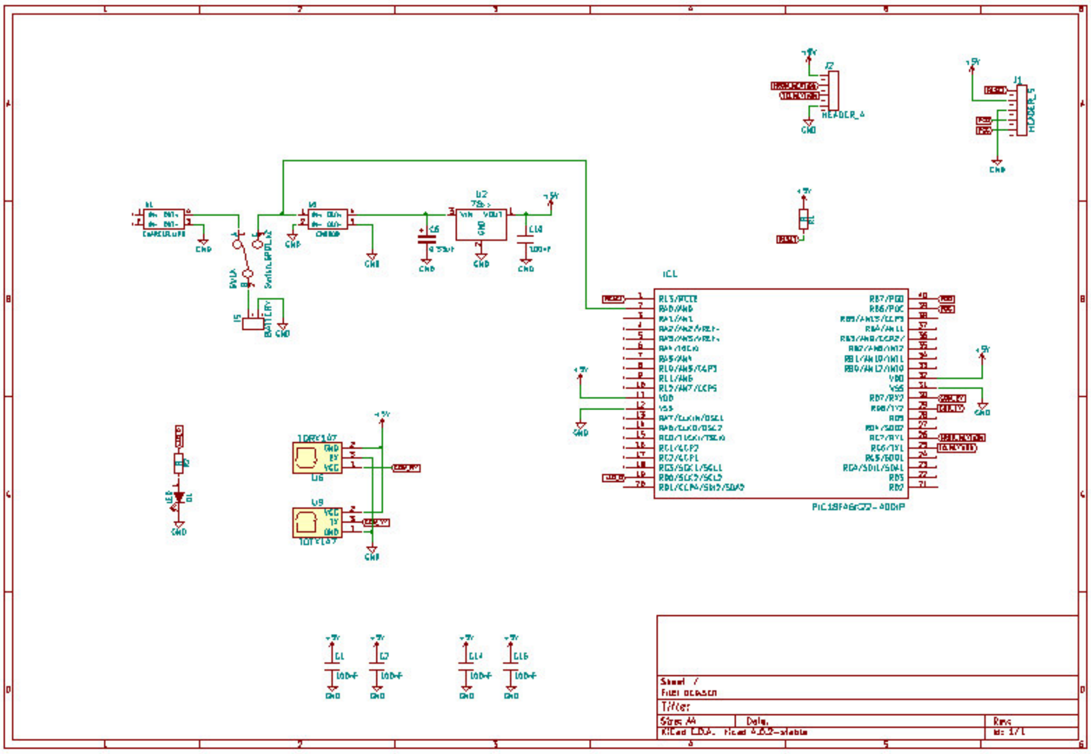

Figura 58. Diseño esquemático de la tarjeta del módulo remoto de control
Fuente: Elaboración propia

En el software Kicad se diseñó la tarjeta analógica en PCB (Figura 59).

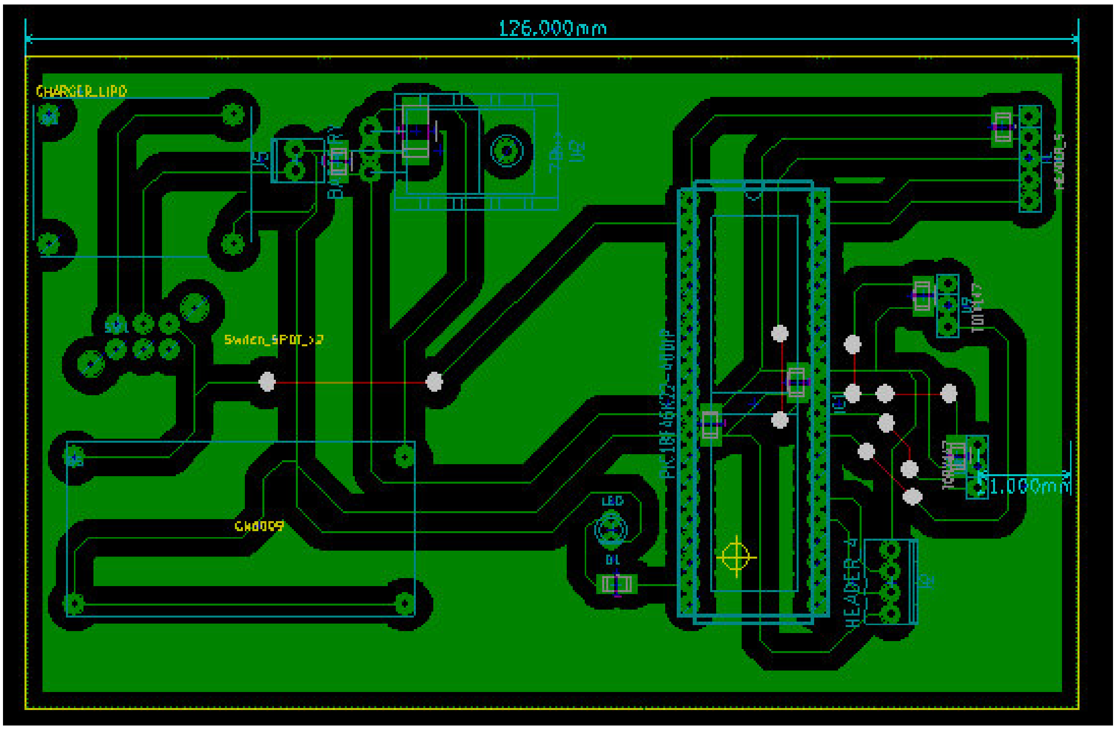

Figura 59. Diseño PCB de la tarjeta del módulo remoto de control
Fuente: Elaboración propia

En el software Kicad se tiene una vista en 3D (Figura 60).

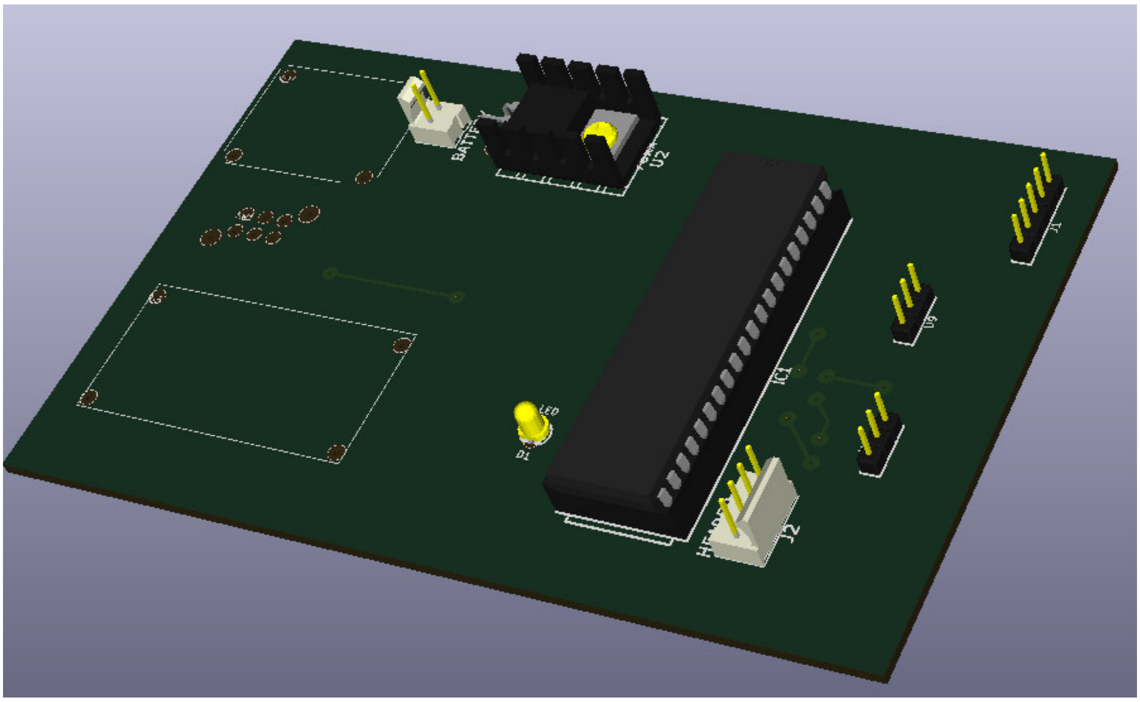

Figura 60. Vista 3D de la tarjeta del módulo remoto de control.
Fuente: Elaboración propia.

La prueba de comunicación se realizó generando pulsos entre el modulo local de control y el módulo principal de control como se observa en la Figura 61. Para la comunicación entre ambos módulos se utilizó las conexiones estándar de transmisión y recepción Toslink, y la fibra óptica.

Figura 61. Pruebas de comunicación entre ambos módulos
Fuente: Elaboración propia

El tipo de comunicación es en serie, consiste en enviar bits la data de manera secuencial a través de una línea en la transmisión y otra en la recepción (fibra óptica). Ya que la transmisión de información es a través de una línea se requiere usar sistemas de codificación, en este caso se utilizó la sincronización de bit. El receptor requiere saber exactamente el inicio y final del tiempo a transmitir cada data, por ejemplo en la Figura 62 se representa la medición del campo magnético en un instante determinado, donde la letra X indica que se inicia la medición, luego se tiene en cada bit por separado el valor del campo terminando con la letra Y que nos indica el final de la medición. Finalmente este paquete de datos es enviado al módulo remoto de control para que este muestre los valores en la pantalla LCD. Así consecutivamente se realizará las próximas mediciones.

X	0	.	5	6	4	Y

Figura 62. Paquete de datos de una medición en un tiempo determinado

Fuente: Elaboración propia.

Costo de fabricación del módulo remoto de control

La tabla 13 presenta los costos de los materiales utilizados en la implementación de la estructura de la caja acrílica y piezas.

Tabla 13 *Costo de implementación del módulo remoto de control*

Materiales	Cantidad	Subtotal (S/.)	Total (S/.)
Pantalla LCD Nextion NX4024T032-011	1	200.00	200.00
Conectores TOSLINK – Fibra óptica	3	10.00	30.00
Cable de fibra óptica 5 metros	2	25.00	50.00
Microcontrolador 18F46K22	1	60.00	60.00
Módulo regulador de voltaje 7805	1	30.00	30.00
Módulo cargador de batería	1	30.00	30.00
Batería ion litio 3.7 v 3300 mAmp/H	1	15.00	15.00
Módulo Step up XL6009	1	25.00	25.00
Total		502.50	

Capítulo 4

Resultados y evaluación de prototipo

Luego de la implementación, las pruebas realizadas a cada sensor y a los módulos que constituyen en el prototipo, se procedió a realizar las pruebas de funcionamiento y contrastar las mediciones entre el prototipo y el equipo Narda NBM 550.

Se eligió el equipo NARDA NBM 550 ya que nuestro equipo de referencia EFA 300 se encontraba descalibrado. Por lo tanto al tener un equipo calibrado como el NARDA NBM 550 nos certificó una medición confiable para poder realizar nuestras pruebas de comparación con seguridad.

Medición de campos magnéticos provenientes de la bobina Helmholtz mediante el equipo de referencia NBM 550 y el prototipo de medición.

Para contrastar las mediciones hechas por el prototipo y el equipo Narda NBM 550, se requiere diseñar una bobina Helmholtz para simular el flujo magnético requerido y de esta forma calibrar el prototipo teniendo como referencia el equipo Narda.

Una forma útil de calibrar los sensores de campo magnético es el uso de una bobina de Helmholtz. Esto consiste de un par de bobinas multiespira planas con el eje central perpendicular a sus superficies. Las bobinas están apartadas por la distancia de un radio, y ambas llevan la misma corriente en la misma dirección. Este tipo de sistema de bobina genera un campo magnético uniforme sobre un volumen conocido entre las bobinas. (Figura 63)

Figura 63. Bobina Helmholtz
Fuente: Elaboración propia

Para el diseño de la bobina de Helmholtz descrito anteriormente, la densidad de flujo es dada por la siguiente ecuación.

$$B = 1.8\, x\, 10^{-6}\ \frac{NI}{D}$$

Donde:

- B = Densidad de flujo magnético (T) en el punto medio entre las dos bobinas sobre su línea central común.
- N = Número de espiras en cada una de las bobinas
- D = Diámetro de cada bobina = 2 r (m)
- I = Corriente (A) fluyendo a través de los alambres en la bobina

La implementación de la Bobina Helmholtz tiene las siguientes características:

- Diámetro = 72 cm (radio 36 cm)
- Calibre del cable: 14
- Numero de espiras: 76 vueltas

Teniendo en cuenta que el campo magnético que se genera en el interior de estas bobinas está en función de la corriente que circula por ellas, debido a ello se implementó un sistema de generación de campo magnético usando los siguientes componentes: (Figura 64)

- ❖ Variac.
- ❖ Bobina con cable de cobre calibre 14.
- ❖ Llave termomagnética

Figura 64. Sistema de generación de campo magnético.
Fuente: Elaboración propia

Luego de establecer nuestro de sistema de generación de campo magnético mediante la bobina Helmholtz, el variac y la llave termomagnética para cuestiones de seguridad se procedió a realizar las mediciones con el equipo NARDA NBM 550. En la Figura 65 se muestra el montaje del inicio de las mediciones.

El control de la corriente se realizó mediante la pinza amperimétrica, en el caso del voltaje con el multímetro con el fin de corroborar la exactitud del valor que muestra la pantalla del variac y el medidor NBM 550 se equipa con la sonda EHP-50F la cual es exclusiva para realizar pruebas en el rango de baja frecuencia (1 Hz a 400 kHz). La frecuencia que se trabajó para este tipo de campo es específicamente de 60 Hz.

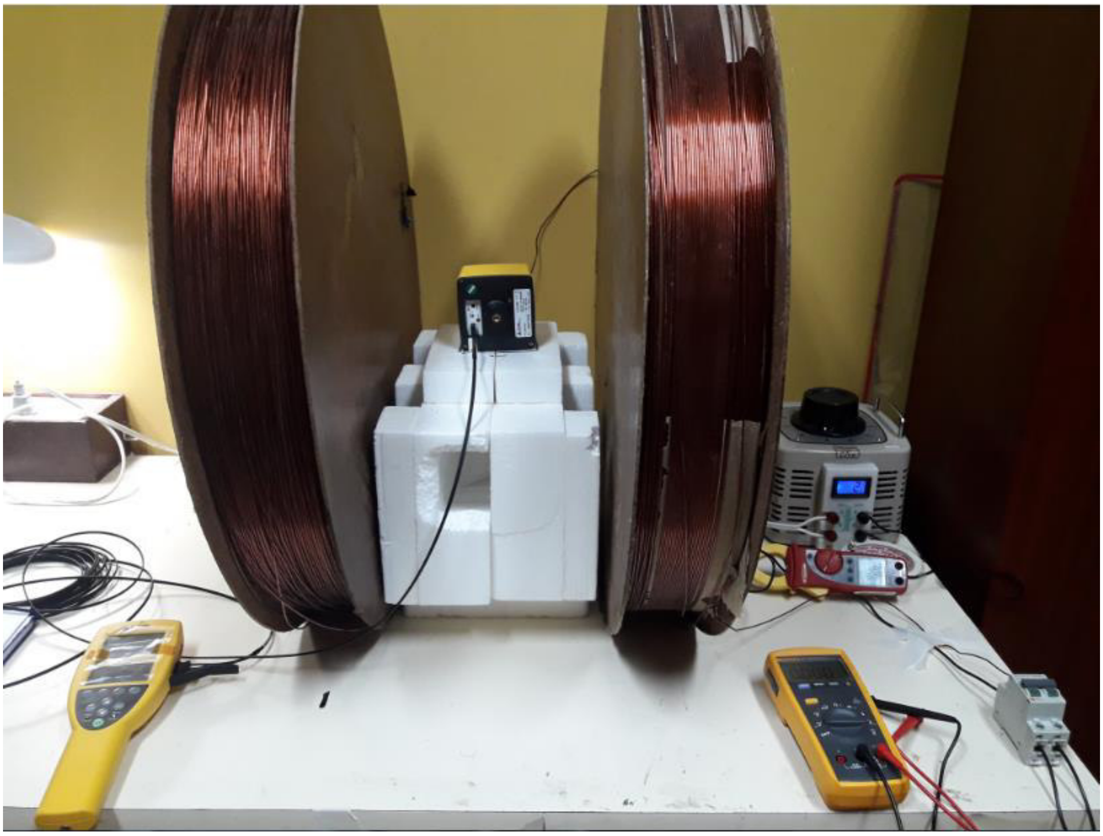

Figura 65. Montaje de equipos para la medición y control del flujo del campo magnético
Fuente: Elaboración propia

En la tabla 14 se muestra las principales características de la sonda EHP-50F, las especificaciones técnicas completas tanto de la sonda como el equipo NBM-550 se muestra en el Apéndice C.

Tabla 14

Principales características de la sonda EHP-50F

Especificaciones técnicas	
Rango de frecuencias	1 Hz hasta 400 kHz
Rango dinámico	>105 dB
Rango de medición campo eléctrico (E)	5 mV/m hasta 100 kV/m
Rango de medición campo magnético (M)	0.3 nT hasta 10 mT
Rango de temperatura de operación	-20 °C hasta + 55°C
Estándares	2013/35/EU, ICNIRP 2010, ICNIRP 1998
Peso	550 g
Dimensiones	92 mm x 92 mm x 109 mm

Nota: Elaboración propia

En la Figura 66 se muestra el montaje para la medición del campo magnético a 60 Hz mediante el módulo sensor.

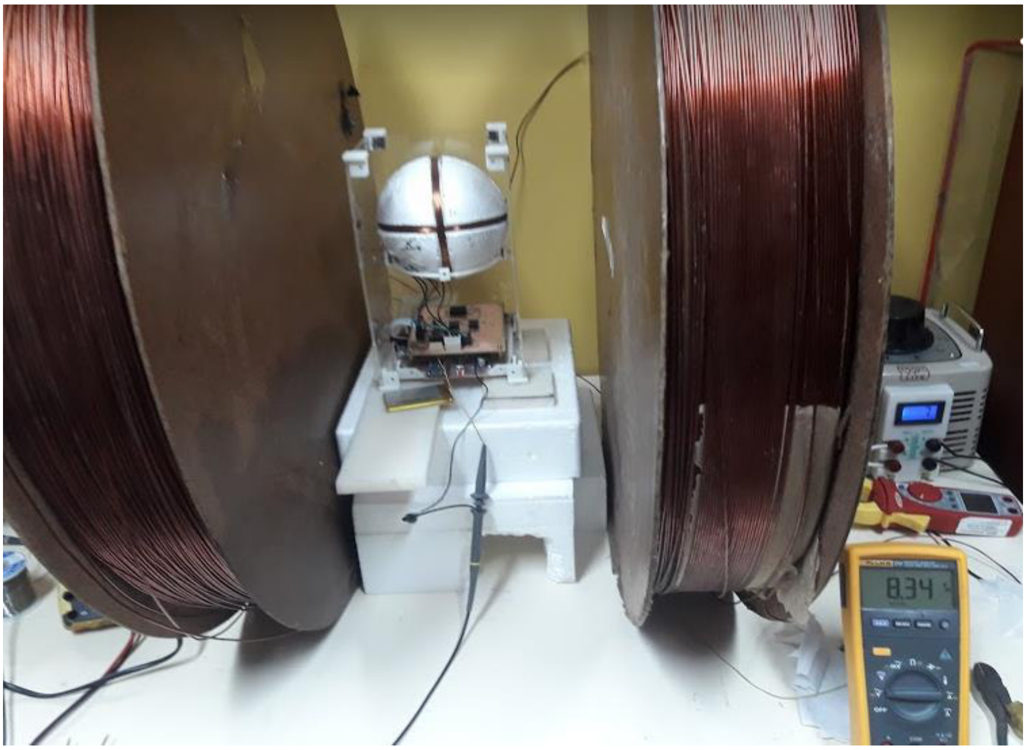

Figura 66. Montaje del prototipo para la medición y control del flujo del campo magnético
Fuente: Elaboración propia

Para esta prueba se requirió un osciloscopio para poder visualizar la señal filtrada y amplificada. Según las pruebas hechas se obtuvo una señal limpia y correctamente amplificada como se observa en la Figura 67.

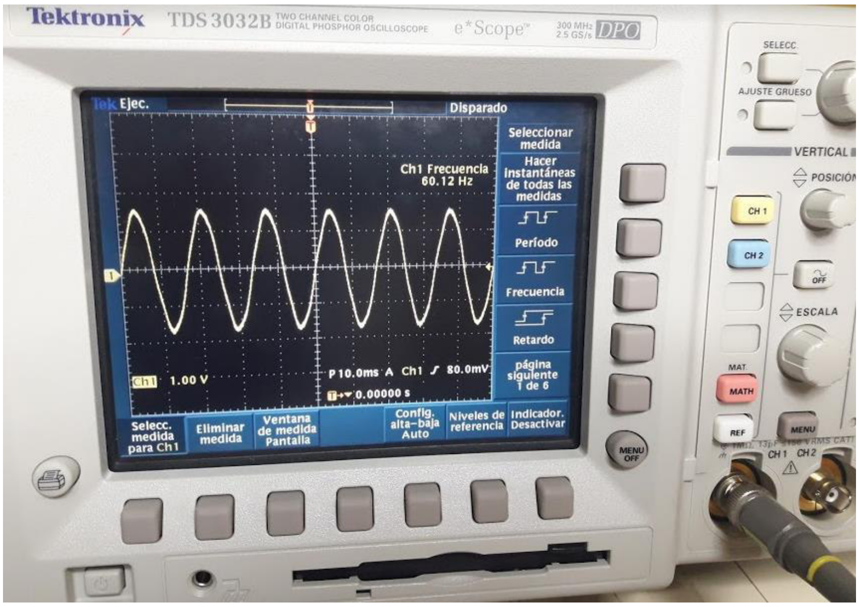

Figura 67. Señal filtrada e amplificada
Fuente: Elaboración propia

Resultados de las pruebas de medición del campo magnético del equipo NARDA NBM 550 y Prototipo implementado.

El protocolo de medición que se consideró para realizar las mediciones consistió en instalar la sonda EHP-50F en el eje central de las bobinas Helmholtz y ubicarse a una cierta distancia para tener mediciones correctas como se muestra en la Figura 68.

La generación del flujo del campo magnético fueran hasta 1 mT para una frecuencia de 60 Hz que está al límite según las recomendaciones ICNIRP 2010. Para realizar la variación del flujo del campo magnético se usó el Variac que reguló la corriente de las Bobinas Helmholtz. Las especificaciones técnicas de este equipo se pueden observar en el Apéndice D.

Figura 68. Sonda EHP-50F instalada en el eje central de las bobinas
Fuente: Elaboración propia

Las mediciones se iniciaron con el valor 0.239 mT según indica el equipo NBM550, este flujo del campo magnético es producido por un voltaje de entrada 0.967v y 100 mA.

Para generar en las bobinas un flujo de campo magnético 0.0417 mT se requirió una corriente de 200 mA con 75 vueltas de la bobina Helmholtz. En el medidor NBM 550 se obtuvo un valor de 0.0418 mT, este valor se aprecia en la Figura 69.

B: Flujo de campo magnético en las bobinas

$$B = 1.8\ x\ 10^{-6}\ \frac{NI}{D}$$

$$B\ = 1.8\ x\ 10^{-6}\ \frac{(\ 75)(200\ mA)}{72\ cm}$$

$$B = 0.0417\ mT$$

Figura 69. Nivel de campo producido por una corriente de 600 mA
Fuente: Elaboración propia

Para generar en las bobinas un flujo de campo magnético 0.298 mT se requirió una corriente de 1600 mA con 75 vueltas de la bobina Helmholtz. En el medidor NBM 550 se obtuvo un valor de 0.2983 mT, este valor se aprecia en las Figuras 70.

B: Flujo de campo magnético en las bobinas

$$B = 1.8 \, x \, 10^{-6} \, \frac{NI}{D}$$

$$B \; = 1.8 \, x \, 10^{-6} \, \frac{(\,75)(1600 \, mA)}{72 \, cm}$$

$$B = 0.298 \, mT$$

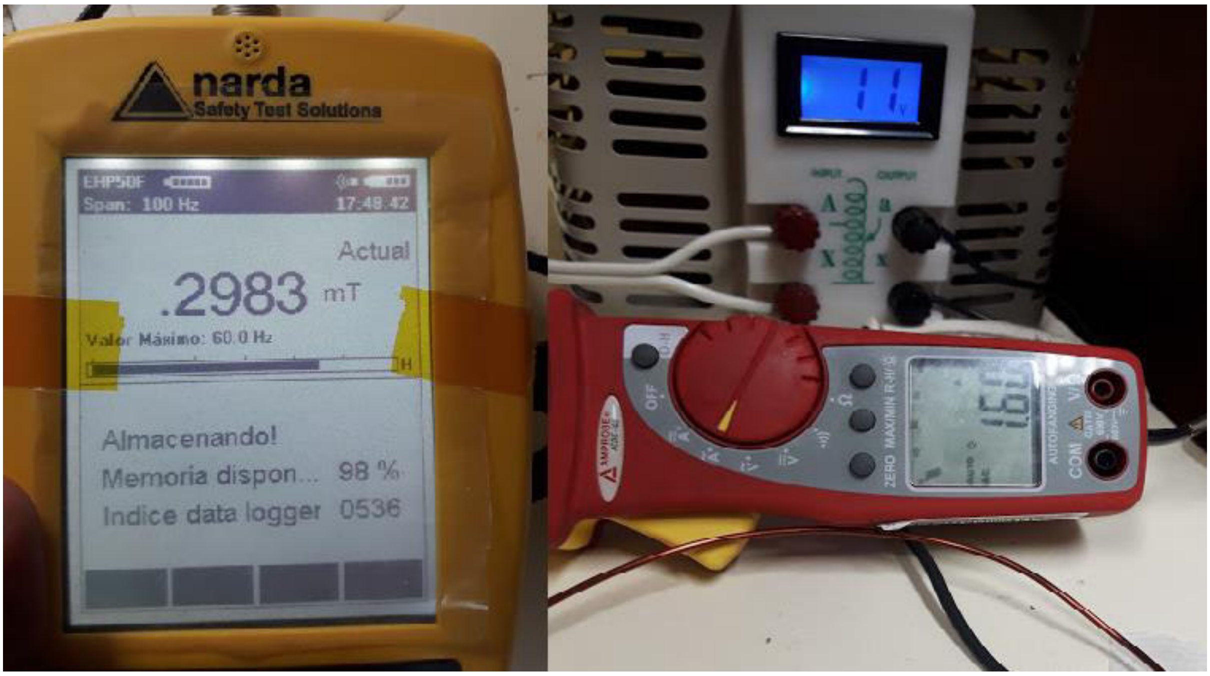

Figura 70. Nivel de campo producido por una corriente de 1600 mA
Fuente: Elaboración propia

Finalmente para generar en las bobinas un flujo de campo magnético 1 mT se requirió una corriente de 5.4 Amp. con 75 vueltas de la bobina Helmholtz. En el medidor NBM 550 se obtuvo un valor de 1.002 mT, este valor se aprecia en las Figuras 71.

B: Flujo de campo magnético en las bobinas

$$B = 1.8\,x\,10^{-6}\,\frac{NI}{D}$$

$$B\;=1.8\,x\,10^{-6}\,\frac{(\,75)(5.4\,Amp)}{72\,cm}$$

$$B = 1\,mT$$

Figura 71. Nivel de campo producido por una corriente de 600 mA
Fuente: Elaboración propia

Luego de la calibración del equipo se realizaron 50 mediciones, tanto en el ambiente del laboratorio, como en un espacio abierto, en ambos casos utilizando el generador variable de campo magnético pero haciendo una comparación con el equipo NARDA NBM 550. En la Tabla 15 se aprecia ambos valores medidos por el equipo NBM 550 y el prototipo. (Figura 72)


Figura 72. Medición del campo magnético mediante el prototipo
Fuente: Elaboración propia

Tabla 15

Mediciones de campo magnético por el equipo NBM550 y prototipo.

Voltaje en la bobina (v)	**I(mA)**	**B(NBM 550)mT**	**B prototipo mT (con K)**	**B prototipo mT (sin K)**
0.967	100	0.0239	0.0211	0.000959091
1.735	200	0.0417	0.039	0.001772727
2.485	300	0.0576	0.0535	0.002431818
3.27	400	0.0785	0.072	0.003272727
4.02	500	0.0895	0.0874	0.003972727
4.735	600	0.1139	0.11	0.005
5.485	700	0.1367	0.132	0.006
6.32	800	0.1532	0.151	0.006863636
7.07	900	0.1776	0.172	0.007818182
7.95	1000	0.1913	0.189	0.008590909
8.7	1100	0.21	0.208	0.009454545
9.44	1200	0.2284	0.203	0.009227273
10.19	1300	0.2467	0.224	0.010181818
10.85	1400	0.2625	0.259	0.011772727
11.6	1500	0.2756	0.2689	0.012222727
12.36	1600	0.2983	0.285	0.012954545
13.11	1700	0.3217	0.318	0.014454545
13.77	1800	0.3359	0.3267	0.01485
14.45	1900	0.3519	0.348	0.015818182
15.35	2000	0.3691	0.356	0.016181818
16.1	2100	0.3823	0.38	0.017272727
16.93	2200	0.4056	0.399	0.018136364
17.68	2300	0.422	0.42	0.019090909
18.25	2400	0.441	0.427	0.019409091
19.05	2500	0.467	0.454	0.020636364
19.97	2600	0.4794	0.461	0.020954545
20.72	2700	0.496	0.479	0.021772727
21.5	2800	0.5139	0.502	0.022818182
22.24	2900	0.535	0.528	0.024
23.02	3000	0.5531	0.5479	0.024904545
23.77	3100	0.574	0.571	0.025954545
24.59	3200	0.5913	0.588	0.026727273
25.34	3300	0.612	0.61	0.027727273
26.13	3400	0.6281	0.6201	0.028186364
26.88	3500	0.645	0.641	0.029136364
27.61	3600	0.6633	0.661	0.030045455
28.36	3700	0.6834	0.6809	0.03095
29.24	3800	0.7021	0.7	0.031818182
29.99	3900	0.7236	0.7201	0.032731818
30.63	4000	0.7367	0.732	0.033272727
31.38	4100	0.7546	0.75	0.034090909

32.39	4200	0.7751	0.768	0.034909091
33.14	4300	0.792	0.788	0.035818182
33.81	4400	0.8136	0.809	0.036772727
34.56	4500	0.826	0.823	0.037409091
35.2	4600	0.8484	0.843	0.038318182
35.946	4700	0.8678	0.862	0.039181818
37.01	4800	0.8905	0.889	0.040409091
37.76	4900	0.9123	0.908	0.041272727
38.47	5000	0.9253	0.922	0.041909091
39.22	5100	0.945	0.941	0.042772727
40.09	5200	0.9638	0.9609	0.043677273
40.84	5300	0.985	0.981	0.044590909
41.6	5400	1.002	1	0.045454545
42.35	5500	1.021	1.018	0.046272727
43.21	5600	1.04	1.037	0.047136364

En la Figura 73 se observa que las mediciones realizas por el equipo NARDA NBM 500 y el prototipo son similares ya que se aplicó un factor de correlación K = 22 sobre la columna “B prototipo mT (sin K)”. Los valores medidos por el prototipo sin considerar la constante K se observa en la línea de color plomo.

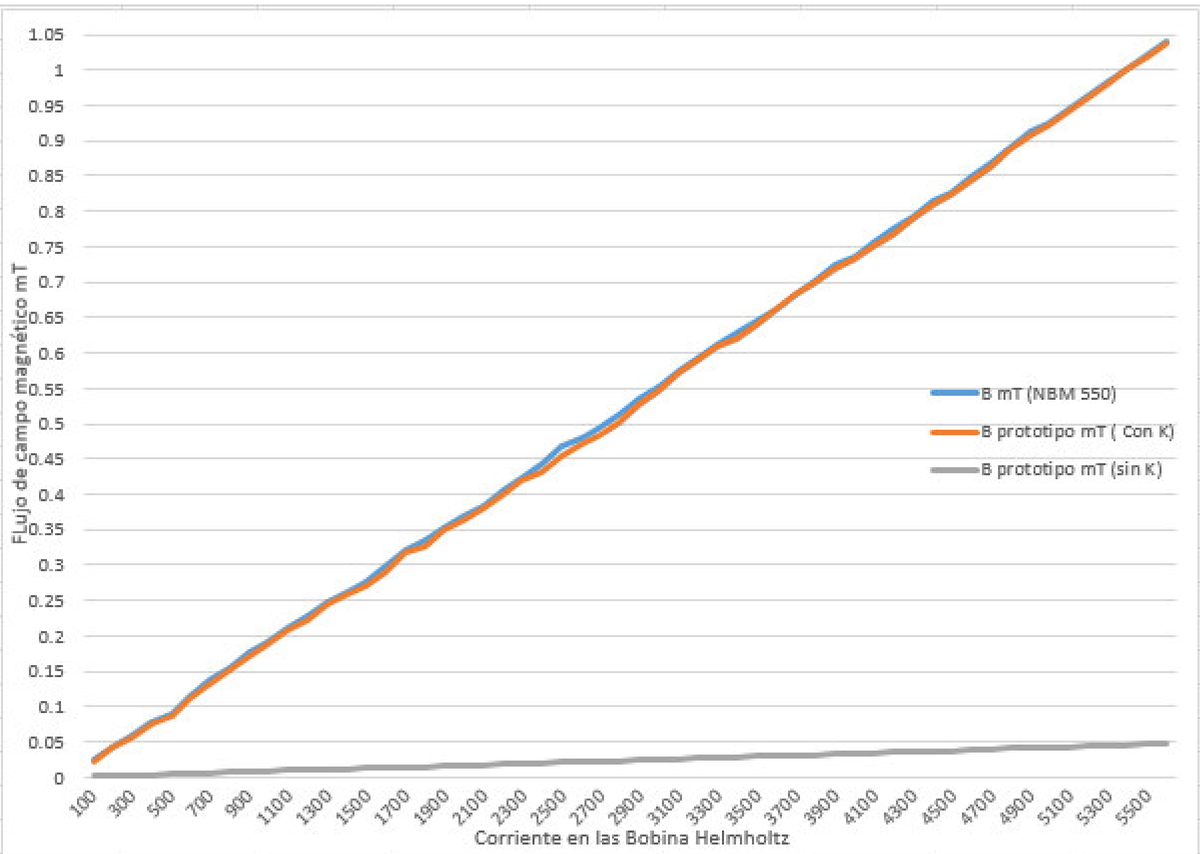

Figura 73. Semejanza de los valores del campo magnético usando la constante K
Fuente: Elaboración propia

$$B = B\ prototipo * K$$

El valor de la constante K tendrá el valor de 22, ya que era el número más conveniente para obtener un valor similar al valor de equipo NARDA NBM 550. Por ejemplo, se fija un valor de corriente 500 mA, el valor obtenido en el NBM 550 es 0.0895 mT y en el prototipo sin multiplicar la constante K es 0.003972727 mT.

Entonces:

$$K = \frac{0.0895\ mT}{0.003972727\ mT}$$

$$K = 22$$

Así sucesivamente sucede con los otros valores en la tabla 21.

En las mediciones se aprecia que las diferencias de medidas entre el prototipo y el NBM 550 son en porcentaje menores al 3% con respecto al NBM 550, eso nos da una confiabilidad de las mediciones del prototipo. En la tabla 16 se aprecia con más detalle estos valores.

$$Diferencia = B_{NBM\ 550} - B_{Prototipo}$$

$$Diferencia\ \% = \frac{Diferencia}{B_{NBM\ 550}} * 100$$

Un ejemplo de la diferencia en porcentaje tenemos los siguientes valores:

- B (NBM 550) = 0.0239 mT
- B (prototipo) = 0.0232 mT

$$Diferencia\ \% = \frac{0.0239\ \mathrm{mT} - 0.0232\ \mathrm{mT}}{0.0239\ mT} * 100$$

$$Diferencia\ \% = 2.9288\ \%$$

Tabla 16

Porcentaje de diferencia de los valores medidos por el NBM 550 y prototipo

B(NBM 550)mT	**B prototipo mT (con K)**	**Diferencia**	**Diferencia %**
0.0239	0.0232	0.0007	2.92887029
0.0417	0.0409	0.0008	1.91846523
0.0576	0.0559	0.0017	2.95138889
0.0785	0.0765	0.002	2.5477707
0.0895	0.0874	0.0021	2.34636872
0.1139	0.1119	0.002	1.75592625
0.1367	0.1329	0.0038	2.7798098
0.1532	0.151	0.0022	1.43603133
0.1776	0.172	0.0056	3.15315315
0.1913	0.189	0.0023	1.20230005
0.21	0.208	0.002	0.95238095
0.2284	0.223	0.0054	2.3642732
0.2467	0.244	0.0027	1.0944467
0.2625	0.259	0.0035	1.33333333
0.2756	0.2689	0.0067	2.43105951
0.2983	0.291	0.0073	2.4472008
0.3217	0.318	0.0037	1.15013988
0.3359	0.3267	0.0092	2.73891039
0.3519	0.348	0.0039	1.10826939
0.3691	0.362	0.0071	1.92359794
0.3823	0.38	0.0023	0.60162176

0.4056	0.399	0.0066	1.62721893
0.422	0.42	0.002	0.47393365
0.441	0.431	0.01	2.2675737
0.467	0.454	0.013	2.78372591
0.4794	0.471	0.0084	1.75219024
0.496	0.485	0.011	2.21774194
0.5139	0.502	0.0119	2.31562561
0.535	0.528	0.007	1.30841121
0.5531	0.5479	0.0052	0.94015549
0.574	0.571	0.003	0.52264808
0.5913	0.588	0.0033	0.55809234
0.612	0.61	0.002	0.32679739
0.6281	0.6201	0.008	1.27368253
0.645	0.641	0.004	0.62015504
0.6633	0.661	0.0023	0.34675109
0.6834	0.6809	0.0025	0.36581797
0.7021	0.7	0.0021	0.29910269
0.7236	0.7201	0.0035	0.48369265
0.7367	0.732	0.0047	0.63798018
0.7546	0.75	0.0046	0.60959449
0.7751	0.768	0.0071	0.91601084
0.792	0.788	0.004	0.50505051
0.8136	0.809	0.0046	0.5653884
0.826	0.823	0.003	0.36319613
0.8484	0.843	0.0054	0.63649222
0.8678	0.862	0.0058	0.66835676
0.8905	0.889	0.0015	0.16844469
0.9123	0.908	0.0043	0.47133618
0.9253	0.922	0.0033	0.35664109
0.945	0.941	0.004	0.42328042
0.9638	0.9609	0.0029	0.3008923
0.985	0.981	0.004	0.40609137
1.002	1	0.002	0.1996008
1.021	1.018	0.003	0.29382958
1.04	1.037	0.003	0.28846154

Algunas mediciones se realizaron después de varias semanas, y se observa que el equipo no se ha descalibrado, mantiene los mismos porcentajes de las diferencias, esto da una muestra de la confiabilidad del equipo.

Finalmente se usó un osciloscopio para corroborar si el proceso de filtrado, amplificación y conteo de frecuencias se está realizando correctamente. En la Figura 74 se observa un correcto funcionamiento.

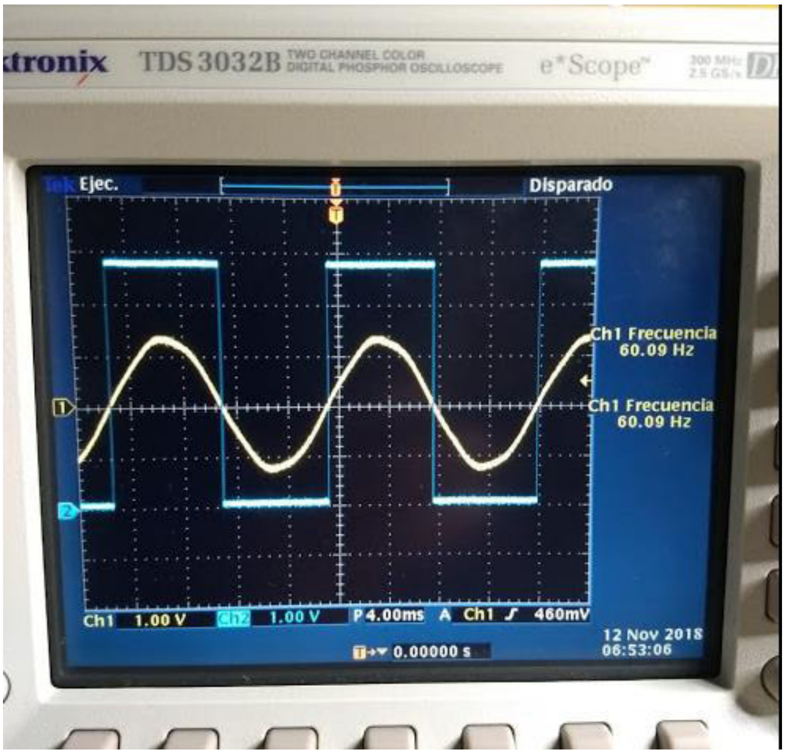

Figura 74 Filtrado, amplificación y conteo de frecuencia de la señal captada
Fuente: Elaboración propia

Resultados de las pruebas de medición del campo eléctrico del equipo NARDA NBM 550 y Prototipo implementado.

En las pruebas realizadas se montó un sistema de generación de campo eléctrico mediante 2 placas paralelas de dimensiones de 30 cm x 30 cm. Este a su vez es conectado a un generador de funciones con el fin de simular campos eléctricos a distintas frecuencias. Como se indicó en el capítulo anterior, solo se realizó mediciones en el rango de frecuencias de 300 Hz hasta 32 kHz. (Figura 75)

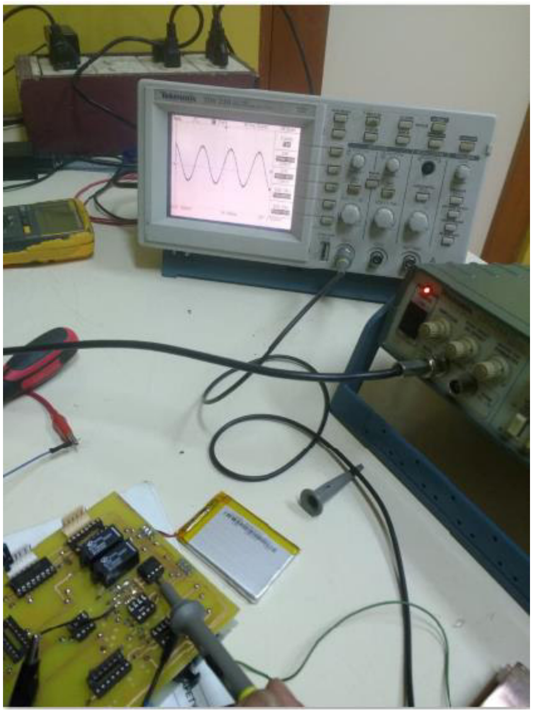

Figura 75. Montaje para la generación de campo eléctrico
Fuente: Elaboración propia

Para la medición del campo eléctrico se debe considerar las siguientes sugerencias:

- Para evitar perturbaciones en la medición del campo eléctrico, se recomienda que el usuario se encuentre ubicado a una distancia mínima de 2.5 m de la sonda.
- Al realizar mediciones de la intensidad de campos eléctricos que representen el campo perturbado en una ubicación dada, el área debe estar libre, en la medida de lo posible, de otras líneas de conducción eléctrica, torres, árboles, cercas, arbustos grandes u otras irregularidades. En nuestro caso, las pruebas se realizaron en laboratorio pero se consideró tener el espacio libre.
- Es necesario ubicar las coordenadas geográficas haciendo uso de GPS, los puntos de medición que ya hayan sido definidos en la estrategia de muestreo (Para futuras mediciones).
- Realizar un detalle mediante croquis, fotografías y vistas del lugar, las particularidades de los sitios expuestos a las radiaciones no ionizantes (Para futuras mediciones).

- ❖ Tomar evidencia fotográfica de las torres, postes y equipo de medición para documentar el trabajo de medición (Para futuras mediciones).
- ❖ Proceder al encendido del equipo y fijación de las unidades y el tiempo de medición de acuerdo al manual del equipo (Para futuras mediciones).

En la Figura 76 se instala la sonda EHP-50F para iniciar la medición del campo eléctrico a distintas frecuencias, regulado por el generador de funciones.

Figura 76. Montaje de la sonda EHP-50F para la generación de campo eléctrico
Fuente: Elaboración propia

La prueba se inició generando una señal de 300 Hz, obteniendo un valor en el NBM 550 de 424.8 V/m como se observa en la Figura 77, en el prototipo se obtiene un valor 5.557 V/m sin el factor de corrección, en la Figura 78 se aprecia el filtrado de la señal a dicha frecuencia.

Figura 77. Medición del campo eléctrico a 300 Hz
Fuente: Elaboración propia

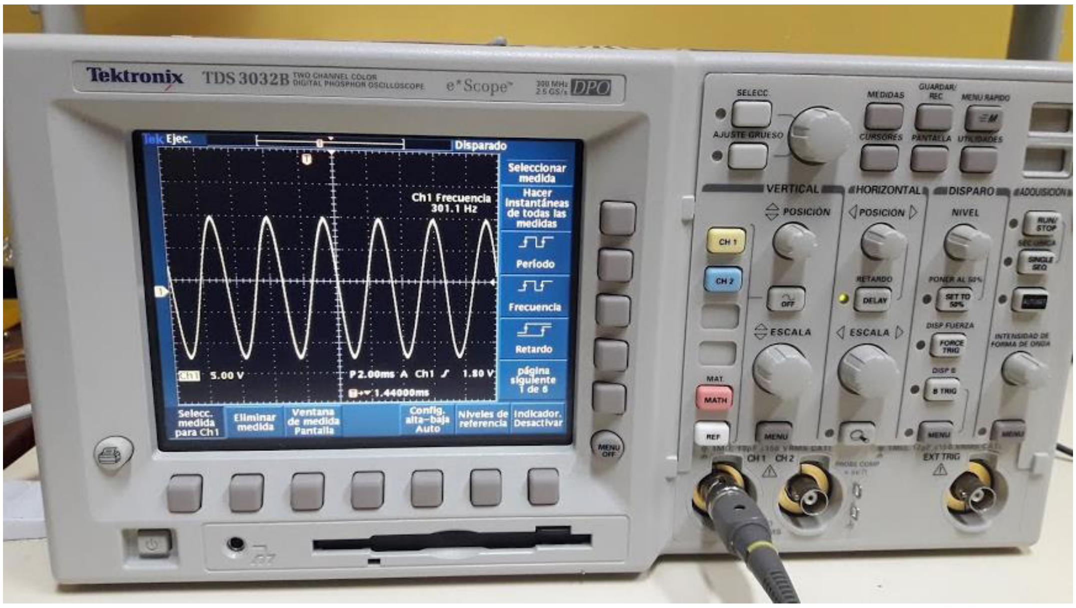

Figura 78. Filtrado de una señal de campo eléctrico a 300 Hz
Fuente: Elaboración propia

Siguiendo con las pruebas en la Figura 79 se observa la medición realizada del campo eléctrico con una frecuencia de 10 kHz, obteniendo un valor del campo eléctrico de 428.2

V/m, en el prototipo se obtuvo un valor de 5.60 V/m sin el factor de corrección. En la Figura 80 se observa la señal filtrada.

Figura 79. Medición del campo eléctrico a 10 kHz
Fuente: Elaboración propia

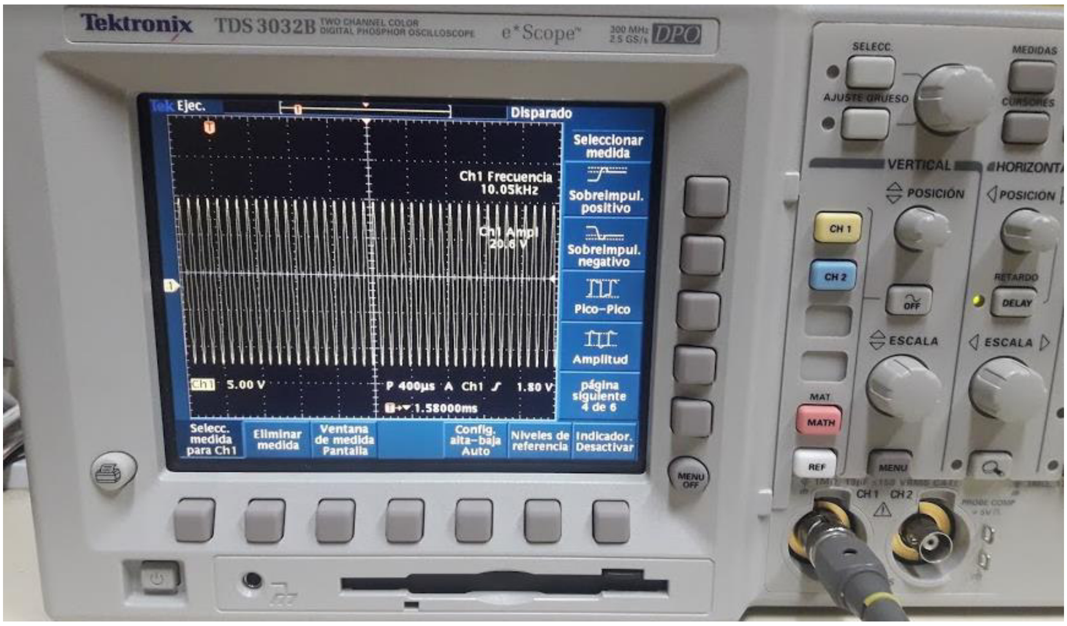

Figura 80. Filtrado de una señal de campo eléctrico a 10 kHz
Fuente: Elaboración propia

Continuando las pruebas, en la Figura 81 se observa la medición realizada del campo eléctrico con una frecuencia de 20 kHz, obteniendo un valor del campo eléctrico de 428.8 V/m, en el prototipo se obtuvo un valor de 5.611 V/m sin el factor de corrección. En la Figura 82 se observa la señal filtrada.

Figura 81. Medición del campo eléctrico a 20 kHz
Fuente: Elaboración propia

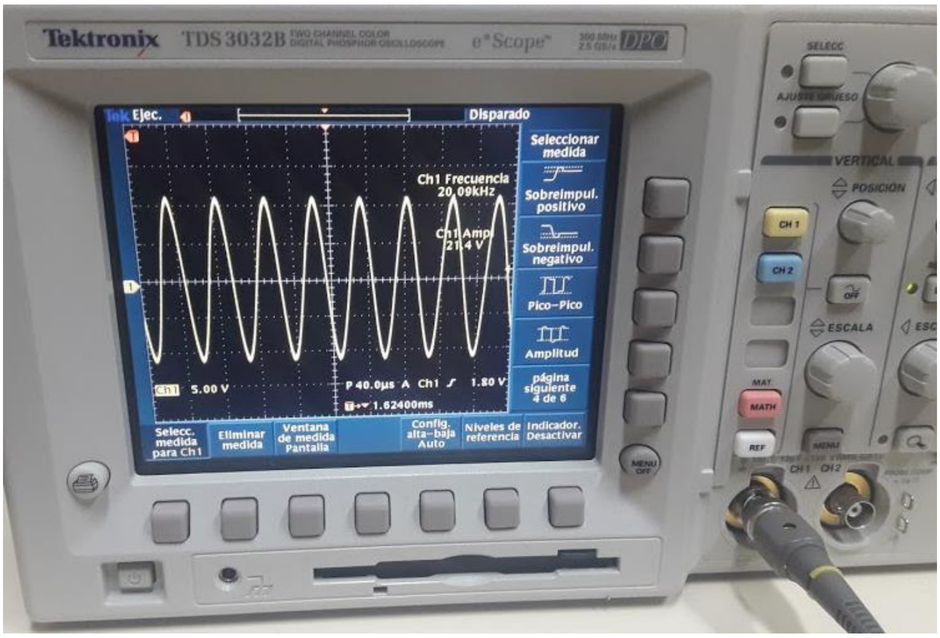

Figura 82. Filtrado de una señal de campo eléctrico a 20 kHz
Fuente: Elaboración propia

Debido que el límite superior de medición de es 32 kHz se realizó la última prueba generando una señal de esta frecuencia entre las placas paralelas. En la figura 83 se observa la medición realizada con el NBM 550 obteniendo un valor de 424.9 V/m y en el prototipo el valor del campo eléctrico sin factor de corrección de 5.57 V/m. En la figura 84 se observa que se llegó realizar el filtrado de esta señal satisfactoriamente.

Figura 83. Medición del campo eléctrico 32 kHz
Fuente: Elaboración propia

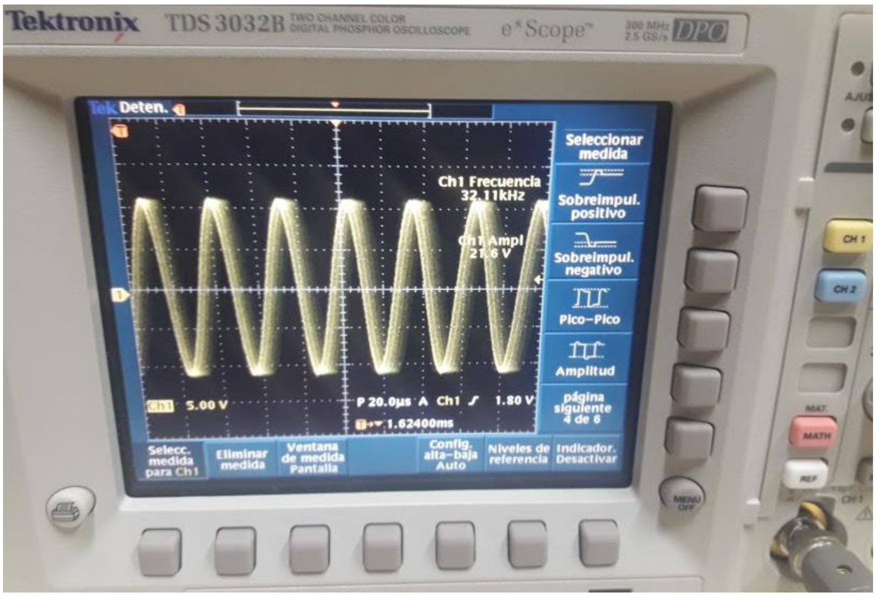

Figura 84. Filtrado de una señal de campo eléctrico a 32 kHz
Fuente: Elaboración propia

En la Tabla 17 se aprecia con más detalle de las mediciones realizadas del campo eléctrico con el equipo NARDA NBM 550 y el prototipo medidor de campo. Estas mediciones se realizaron en el laboratorio cumpliendo las recomendaciones establecidas.

Tabla 17

Mediciones de campo eléctrico por el equipo NBM550 y prototipo

Voltaje generador	**Frecuencia (Hz)**	**E (NBM 550) V/m**	**E prototipo V/m (con K)**	**E prototipo V/m (sin K)**
21.5	300	424.8	416.84	5.557866667
21.5	500	426.5	418.9	5.585333333
21.5	1000	424.8	416.84	5.557866667
21.5	1500	429.4	421.25	5.616666667
21.5	2000	428.6	420.75	5.61
21.5	3000	429.4	421.25	5.616666667
21.5	4000	427.4	419.5	5.593333333
21.5	5000	428.4	420.51	5.6068
21.5	6000	429.4	421.25	5.616666667
21.5	7000	427.9	419.94	5.5992
21.5	8000	428.4	420.51	5.6068
21.5	9000	427.9	419.94	5.5992
21.5	10000	428.2	420.46	5.606133333
21.5	11000	424.2	416.12	5.548266667
21.5	12000	427.6	419.76	5.5968
21.5	13000	428.2	420.46	5.606133333
21.5	14000	427.6	419.76	5.5968
21.5	15000	427.3	419.45	5.592666667
21.5	16000	429	420.94	5.612533333
21.5	17000	428.3	420.48	5.6064
21.5	18000	429.6	421.5	5.62
21.5	19000	429.5	421.3	5.617333333
21.5	20000	428.8	420.85	5.611333333
21.5	21000	428.9	420.87	5.6116
21.5	22000	429	420.94	5.612533333
21.5	23000	424.2	416.12	5.548266667
21.5	24000	424.6	416.52	5.5536
21.5	25000	425.3	418.35	5.578
21.5	26000	420.9	414.6	5.528
21.5	27000	423.8	415.6	5.541333333
21.5	28000	424.4	416.5	5.553333333
21.5	29000	424.8	416.84	5.557866667
21.5	30000	425	418.1	5.574666667
21.5	31000	425.8	418.6	5.581333333
21.5	32000	424.9	417.8	5.570666667

En la Figura 85 se observa que las mediciones realizas por el equipo NARDA NBM 500 y el prototipo son similares ya que se aplicó un factor de correlación K = 75 sobre la columna "E prototipo V/m (sin K)". Los valores medidos por el prototipo sin considerar la constante K se observa en la línea de color amarillo.

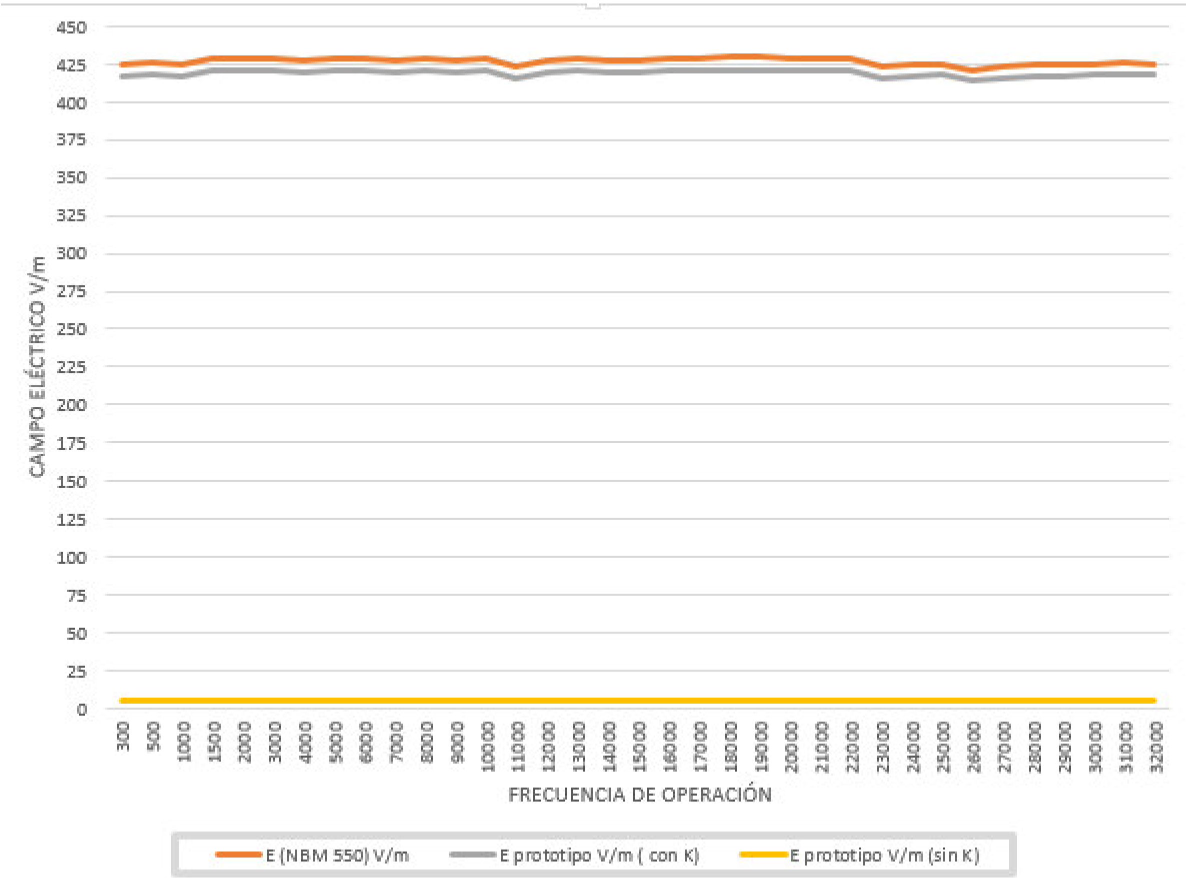

Figura 85. Semejanza de los valores del campo eléctrico usando la constante K
Fuente: Elaboración propia

$$E \ = E\ prototipo * K$$

El valor de la constante K tendrá un valor de 75, ya que era es el número más conveniente para obtener un valor similar al valor de equipo NARDA NBM 550. Por ejemplo, se fija una frecuencia 25 kHz y un voltaje en el generador de funciones de 21.6 volt, el valor obtenido en el NBM 550 es 425.3 V/m y en el prototipo sin multiplicar la constante K es 5.578 V/m.

Entonces:

$$E_{prot}\frac{V}{m} = E_{prot}\frac{V}{m}\ (\sin K) * K$$

$$E_{prot}\frac{V}{m} = 5.578 * 75 = 418.35\frac{V}{m} \approx 425.3\frac{V}{m}$$

Como podemos observar en la ecuación se multiplica la consta K al valor del campo eléctrico sin el factor de corrección obteniendo un valor similar al medidor NARDA NBM 550.

En las mediciones se aprecia que las diferencias de medidas entre el prototipo y el NBM 550 son en porcentaje menores al 3% con respecto al NBM 550, eso nos da una confiabilidad de las mediciones del prototipo. En la tabla 18 se aprecia con más detalle estos valores.

$$Diferencia = E_{NBM\ 550} - E_{Prototipo}$$

$$Diferencia\ \% = \frac{Diferencia}{E_{NBM\ 550}} * 100$$

Un ejemplo de la diferencia en porcentaje tenemos los siguientes valores:

- Frecuencia 20 kHz
- E $_{V/m}$ (NBM 550) = 428.8 V/m
- E $_{V/m}$ (prototipo) = 420.85 V/m

$$Diferencia\ \% = \frac{428.8\ \mathrm{V/m} - 420.85\mathrm{V/m}}{428.8\ V/m} * 100$$

$$Diferencia\ \% = 1.854\ \%$$

Tabla 18

Porcentaje de diferencia de los valores medidos por el NBM 550 y prototipo

Frecuencia (Hz)	E (NBM 550) V/m	E prototipo V/m (con K)	E prototipo V/m (sin K)	Dif (E NBM 550 - E prot)	Dif %
300	424.8	416.84	5.557866667	7.96	1.87382298
500	426.5	418.9	5.585333333	7.6	1.78194607
1000	424.8	416.84	5.557866667	7.96	1.87382298
1500	429.4	421.25	5.616666667	8.15	1.89799721
2000	428.6	420.75	5.61	7.85	1.83154456
3000	429.4	421.25	5.616666667	8.15	1.89799721
4000	427.4	419.5	5.593333333	7.9	1.84838559
5000	428.4	420.51	5.6068	7.89	1.84173669
6000	429.4	421.25	5.616666667	8.15	1.89799721
7000	427.9	419.94	5.5992	7.96	1.86024772
8000	428.4	420.51	5.6068	7.89	1.84173669
9000	427.9	419.94	5.5992	7.96	1.86024772
10000	428.2	420.46	5.606133333	7.74	1.80756656
11000	424.2	416.12	5.548266667	8.08	1.9047619
12000	427.6	419.76	5.5968	7.84	1.83348924
13000	428.2	420.46	5.606133333	7.74	1.80756656
14000	427.6	419.76	5.5968	7.84	1.83348924
15000	427.3	419.45	5.592666667	7.85	1.83711678
16000	429	420.94	5.612533333	8.06	1.87878788
17000	428.3	420.48	5.6064	7.82	1.82582302
18000	429.6	421.5	5.62	8.1	1.88547486
19000	429.5	421.3	5.617333333	8.2	1.90919674
20000	428.8	420.85	5.611333333	7.95	1.85401119
21000	428.9	420.87	5.6116	8.03	1.87223129
22000	429	420.94	5.612533333	8.06	1.87878788
23000	424.2	416.12	5.548266667	8.08	1.9047619
24000	424.6	416.52	5.5536	8.08	1.9029675
25000	425.3	418.35	5.578	6.95	1.63414061
26000	420.9	414.6	5.528	6.3	1.49679259
27000	423.8	415.6	5.541333333	8.2	1.93487494
28000	424.4	416.5	5.553333333	7.9	1.86145146
29000	424.8	416.84	5.557866667	7.96	1.87382298
30000	425	418.1	5.574666667	6.9	1.62352941
31000	425.8	418.6	5.581333333	7.2	1.69093471
32000	424.9	417.8	5.570666667	7.1	1.67098141

Algunas mediciones se realizaron después de varias semanas, y se observa que el equipo no se ha descalibrado, y mantiene los mismos porcentajes de las diferencias, esto nos da una muestra de la confiabilidad del equipo.

Capítulo 5

Conclusiones

- El diseño e implementación del prototipo medidor de campos electromagnéticos se cumplió, corroborándose las mediciones realizadas por el prototipo y el equipo de referencia NARDA NBM550.
- En el sensor del campo magnético la dependencia del ángulo se eliminara considerando tres bobinas en disposición perpendicular unas a otras, consiguiendo de esta forma una disposición isotrópica, es decir, consiguiendo que el valor medido sea independiente de la posición relativa del sensor respecto a las líneas de campo.
- La dependencia con la frecuencia del sensor de campo magnético se modifica introduciendo en la cadena de medida un integrador RC de valor adecuado (que anule la parte compleja de la impedancia del sensor dentro de la banda de frecuencia de funcionamiento)
- Las bobinas del sensor de campo magnético requiere estar apantalladas contra campo eléctrico ("shielding") ya que sino también se acoplaría. La razón por la que hay que apantallar las bobinas contra campo E es porque las bobinas están formadas por hilos metálicos que son buenas antenas para captar dicho campo E, sin contar con la capacidad entre espiras que hace que aumente la efectividad de este acoplamiento.
- En el diseño sensor del campo magnético se debe considerar el área efectiva, tener suficiente sensibilidad aumentando el número de vueltas, conseguir baja capacidad entre las espiras de la bobina, apantallamiento de las bobinas frente a campo eléctricos, posicionamiento preciso de las 3 bobinas para evitar error de isotropía y que mecánicamente sea viable (pequeño y robusto).

- La dependencia del ángulo del sensor del campo eléctrico se cancela poniendo tres condensadores de placas paralelas de manera perpendicular unas a otras, consiguiendo una disposición isotrópica.
- Se recomienda usar integrados importados ya que son confiables en su funcionalidad y de esta forma obtener un mejor proceso de filtrado, amplificación de señales de muy baja frecuencias.
- El prototipo de un medidor de campo magnético y eléctrico de baja frecuencias realiza una medición con valores confiable luego de haber sido corroborado por el equipo NARDA NBM 550 ya que se encuentra calibrado y certificado por el comunidad científica internacional. En el caso del campo magnético se puede realizar mediciones en el rango de 60 Hz hasta 32 kHz y para el campo eléctrico desde 300 Hz hasta 32 kHz.

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Apéndice A: Recomendación ICNIRP 1998

INTERNATIONAL COMMISSION ON NON-IONIZING RADIATION PROTECTION

ICNIRP GUIDELINES

FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC, MAGNETIC AND ELECTROMAGNETIC FIELDS (UP TO 300 GHZ)

PUBLISHED IN: **HEALTH PHYSICS 74 (4):494-522; 1998**

Note: Equation 11 was subsequently amended by the ICNIRP Commission in the 1999 reference book. The amended version is added here at the end of the document.

ICNIRP PUBLICATION – 1998

ICNIRP Guidelines

GUIDELINES FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC, MAGNETIC, AND ELECTROMAGNETIC FIELDS (UP TO 300 GHz)

International Commission on Non-Ionizing Radiation Protection*†

INTRODUCTION

In 1974, the International Radiation Protection Association (IRPA) formed a working group on non-ionizing radiation (NIR), which examined the problems arising in the field of protection against the various types of NIR. At the IRPA Congress in Paris in 1977, this working group became the International Non-Ionizing Radiation Committee (INIRC).

In cooperation with the Environmental Health Division of the World Health Organization (WHO), the IRPA/INIRC developed a number of health criteria documents on NIR as part of WHO's Environmental Health Criteria Programme, sponsored by the United Nations Environment Programme (UNEP). Each document includes an overview of the physical characteristics, measurement and instrumentation, sources, and applications of NIR, a thorough review of the literature on biological effects, and an evaluation of the health risks of exposure to NIR. These health criteria have provided the scientific database for the subsequent development of exposure limits and codes of practice relating to NIR.

At the Eighth International Congress of the IRPA (Montreal, 18–22 May 1992), a new, independent scientific organization—the International Commission on Non-Ionizing Radiation Protection (ICNIRP)—was established as a successor to the IRPA/INIRC. The functions of the Commission are to investigate the hazards that may be associated with the different forms of NIR, develop international guidelines on NIR exposure limits, and deal with all aspects of NIR protection.

Biological effects reported as resulting from exposure to static and extremely-low-frequency (ELF) electric and magnetic fields have been reviewed by UNEP/WHO/IRPA (1984, 1987). Those publications and a number of others, including UNEP/WHO/IRPA (1993) and Allen et al. (1991), provided the scientific rationale for these guidelines.

A glossary of terms appears in the Appendix.

PURPOSE AND SCOPE

The main objective of this publication is to establish guidelines for limiting EMF exposure that will provide protection against known adverse health effects. An adverse health effect causes detectable impairment of the health of the exposed individual or of his or her offspring; a biological effect, on the other hand, may or may not result in an adverse health effect.

Studies on both direct and indirect effects of EMF are described; direct effects result from direct interaction of fields with the body, indirect effects involve interactions with an object at a different electric potential from the body. Results of laboratory and epidemiological studies, basic exposure criteria, and reference levels for practical hazard assessment are discussed, and the guidelines presented apply to occupational and public exposure.

Guidelines on high-frequency and 50/60 Hz electromagnetic fields were issued by IRPA/INIRC in 1988 and 1990, respectively, but are superseded by the present guidelines which cover the entire frequency range of time-varying EMF (up to 300 GHz). Static magnetic fields are covered in the ICNIRP guidelines issued in 1994 (ICNIRP 1994).

In establishing exposure limits, the Commission recognizes the need to reconcile a number of differing expert opinions. The validity of scientific reports has to be considered, and extrapolations from animal experi-

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† During the preparation of these guidelines, the composition of the Commission was as follows: A. Ahlbom (Sweden); U. Bergqvist (Sweden); J. H. Bernhardt, Chairman since May 1996 (Germany); J. P. Césarini (France); L. A. Court, until May 1996 (France); M. Grandolfo, Vice-Chairman until April 1996 (Italy); M. Hietanen, since May 1996 (Finland); A. F. McKinlay, Vice-Chairman since May 1996 (UK); M. H. Repacholi, Chairman until April 1996, Chairman emeritus since May 1996 (Australia); D. H. Sliney (USA); J. A. J. Stolwijk (USA); M. L. Swicord, until May 1996 (USA); L. D. Szabo (Hungary); M. Taki (Japan); T. S. Tenforde (USA); H. P. Jammet (Emeritus Member, deceased) (France); R. Matthes, Scientific Secretary (Germany).

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ments to effects on humans have to be made. The restrictions in these guidelines were based on scientific data alone; currently available knowledge, however, indicates that these restrictions provide an adequate level of protection from exposure to time-varying EMF. Two classes of guidance are presented:

- Basic restrictions: Restrictions on exposure to time-varying electric, magnetic, and electromagnetic fields that are based directly on established health effects are termed "basic restrictions." Depending upon the frequency of the field, the physical quantities used to specify these restrictions are current density (**J**), specific energy absorption rate (SAR), and power density (S). Only power density in air, outside the body, can be readily measured in exposed individuals.
- Reference levels: These levels are provided for practical exposure assessment purposes to determine whether the basic restrictions are likely to be exceeded. Some reference levels are derived from relevant basic restrictions using measurement and/or computational techniques, and some address perception and adverse indirect effects of exposure to EMF. The derived quantities are electric field strength (**E**), magnetic field strength (**H**), magnetic flux density (**B**), power density (**S**), and currents flowing through the limbs (I_L). Quantities that address perception and other indirect effects are contact current (I_C) and, for pulsed fields, specific energy absorption (SA). In any particular exposure situation, measured or calculated values of any of these quantities can be compared with the appropriate reference level. Compliance with the reference level will ensure compliance with the relevant basic restriction. If the measured or calculated value exceeds the reference level, it does not necessarily follow that the basic restriction will be exceeded. However, whenever a reference level is exceeded it is necessary to test compliance with the relevant basic restriction and to determine whether additional protective measures are necessary.

These guidelines do not directly address product performance standards, which are intended to limit EMF emissions under specified test conditions, nor does the document deal with the techniques used to measure any of the physical quantities that characterize electric, magnetic, and electromagnetic fields. Comprehensive descriptions of instrumentation and measurement techniques for accurately determining such physical quantities may be found elsewhere (NCRP 1981; IEEE 1992; NCRP 1993; DIN VDE 1995).

Compliance with the present guidelines may not necessarily preclude interference with, or effects on, medical devices such as metallic prostheses, cardiac pacemakers and defibrillators, and cochlear implants. Interference with pacemakers may occur at levels below the recommended reference levels. Advice on avoiding these problems is beyond the scope of the present document but is available elsewhere (UNEP/WHO/IRPA 1993).

These guidelines will be periodically revised and updated as advances are made in identifying the adverse health effects of time-varying electric, magnetic, and electromagnetic fields.

QUANTITIES AND UNITS

Whereas electric fields are associated only with the presence of electric charge, magnetic fields are the result of the physical movement of electric charge (electric current). An electric field, **E**, exerts forces on an electric charge and is expressed in volt per meter (V m^{-1}). Similarly, magnetic fields can exert physical forces on electric charges, but only when such charges are in motion. Electric and magnetic fields have both magnitude and direction (i.e., they are vectors). A magnetic field can be specified in two ways—as magnetic flux density, **B**, expressed in tesla (T), or as magnetic field strength, **H**, expressed in ampere per meter (A m^{-1}). The two quantities are related by the expression:

$$\mathbf{B} = \mu \mathbf{H}, \qquad (1)$$

where μ is the constant of proportionality (the magnetic permeability); in a vacuum and in air, as well as in non-magnetic (including biological) materials, μ has the value $4\pi \times 10^{-7}$ when expressed in henry per meter (H m^{-1}). Thus, in describing a magnetic field for protection purposes, only one of the quantities **B** or **H** needs to be specified.

In the far-field region, the plane-wave model is a good approximation of the electromagnetic field propagation. The characteristics of a plane wave are:

- The wave fronts have a planar geometry;
- The **E** and **H** vectors and the direction of propagation are mutually perpendicular;
- The phase of the **E** and **H** fields is the same, and the quotient of the amplitude of E/H is constant throughout space. In free space, the ratio of their amplitudes E/H = 377 ohm, which is the characteristic impedance of free space;
- Power density, **S**, i.e., the power per unit area normal to the direction of propagation, is related to the electric and magnetic fields by the expression:

$$\mathbf{S} = \mathbf{EH} = E^2/377 = 377H^2. \qquad (2)$$

The situation in the near-field region is rather more complicated because the maxima and minima of E and H fields do not occur at the same points along the direction of propagation as they do in the far field. In the near field, the electromagnetic field structure may be highly inhomogeneous, and there may be substantial variations from the plane-wave impedance of 377 ohms; that is, there may be almost pure E fields in some regions and almost pure H fields in others. Exposures in the near field are

Table 1. Electric, magnetic, electromagnetic, and dosimetric quantities and corresponding SI units.

Quantity	Symbol	Unit
Conductivity	σ	siemens per meter (S m^{-1})
Current	I	ampere (A)
Current density	**J**	ampere per square meter (A m^{-2})
Frequency	f	hertz (Hz)
Electric field strength	**E**	volt per meter (V m^{-1})
Magnetic field strength	**H**	ampere per meter (A m^{-1})
Magnetic flux density	**B**	tesla (T)
Magnetic permeability	μ	henry per meter (H m^{-1})
Permittivity	ϵ	farad per meter (F m^{-1})
Power density	**S**	watt per square meter (W m^{-2})
Specific energy absorption	SA	joule per kilogram (J kg^{-1})
Specific energy absorption rate	SAR	watt per kilogram (W kg^{-1})

more difficult to specify, because both E and H fields must be measured and because the field patterns are morecomplicated; in this situation, power density is no longer an appropriate quantity to use in expressing exposure restrictions (as in the far field).

Exposure to time-varying EMF results in internal body currents and energy absorption in tissues that depend on the coupling mechanisms and the frequency involved. The internal electric field and current density are related by Ohm's Law:

$$\mathbf{J} = \sigma\mathbf{E}, \tag{3}$$

where σ is the electrical conductivity of the medium. The dosimetric quantities used in these guidelines, taking into account different frequency ranges and waveforms, are as follows:

- Current density, **J**, in the frequency range up to 10 MHz;
- Current, I, in the frequency range up to 110 MHz;
- Specific energy absorption rate, SAR, in the frequency range 100 kHz–10 GHz;
- Specific energy absorption, SA, for pulsed fields in the frequency range 300 MHz–10 GHz; and
- Power density, **S**, in the frequency range 10–300 GHz.

A general summary of EMF and dosimetric quantities and units used in these guidelines is provided in Table 1.

BASIS FOR LIMITING EXPOSURE

These guidelines for limiting exposure have been developed following a thorough review of all published scientific literature. The criteria applied in the course of the review were designed to evaluate the credibility of the various reported findings (Repacholi and Stolwijk 1991; Repacholi and Cardis 1997); only established effects were used as the basis for the proposed exposure restrictions. Induction of cancer from long-term EMF exposure was not considered to be established, and so these guidelines are based on short-term, immediate health effects such as stimulation of peripheral nerves and muscles, shocks and burns caused by touching conducting objects, and elevated tissue temperatures resulting from absorption of energy during exposure to EMF. In the case of potential long-term effects of exposure, such as an increased risk of cancer, ICNIRP concluded that available data are insufficient to provide a basis for setting exposure restrictions, although epidemiological research has provided suggestive, but unconvincing, evidence of an association between possible carcinogenic effects and exposure at levels of 50/60 Hz magnetic flux densities substantially lower than those recommended in these guidelines.

In-vitro effects of short-term exposure to ELF or ELF amplitude-modulated EMF are summarized. Transient cellular and tissue responses to EMF exposure have been observed, but with no clear exposure-response relationship. These studies are of limited value in the assessment of health effects because many of the responses have not been demonstrated *in vivo*. Thus, *in-vitro* studies alone were not deemed to provide data that could serve as a primary basis for assessing possible health effects of EMF.

COUPLING MECHANISMS BETWEEN FIELDS AND THE BODY

There are three established basic coupling mechanisms through which time-varying electric and magnetic fields interact directly with living matter (UNEP/WHO/IRPA 1993):

- coupling to low-frequency electric fields;
- coupling to low-frequency magnetic fields; and
- absorption of energy from electromagnetic fields.

Coupling to low-frequency electric fields

The interaction of time-varying electric fields with the human body results in the flow of electric charges (electric current), the polarization of bound charge (formation of electric dipoles), and the reorientation of electric dipoles already present in tissue. The relative magnitudes of these different effects depend on the electrical properties of the body—that is, electrical conductivity (governing the flow of electric current) and permittivity (governing the magnitude of polarization effects). Electrical conductivity and permittivity vary with the type of body tissue and also depend on the frequency of the applied field. Electric fields external to the body induce a surface charge on the body; this results in induced currents in the body, the distribution of which depends on exposure conditions, on the size and shape of the body, and on the body's position in the field.

Coupling to low-frequency magnetic fields

The physical interaction of time-varying magnetic fields with the human body results in induced electric fields and circulating electric currents. The magnitudes of the induced field and the current density are proportional to the radius of the loop, the electrical conductivity of the tissue, and the rate of change and magnitude of the magnetic flux density. For a given magnitude and frequency of magnetic field, the strongest electric fields are induced where the loop dimensions are greatest. The exact path and magnitude of the resulting current induced in any part of the body will depend on the electrical conductivity of the tissue.

The body is not electrically homogeneous; however, induced current densities can be calculated using anatomically and electrically realistic models of the body and computational methods, which have a high degree of anatomical resolution.

Absorption of energy from electromagnetic fields

Exposure to low-frequency electric and magnetic fields normally results in negligible energy absorption and no measurable temperature rise in the body. However, exposure to electromagnetic fields at frequencies above about 100 kHz can lead to significant absorption of energy and temperature increases. In general, exposure to a uniform (plane-wave) electromagnetic field results in a highly non-uniform deposition and distribution of energy within the body, which must be assessed by dosimetric measurement and calculation.

As regards absorption of energy by the human body, electromagnetic fields can be divided into four ranges (Durney et al. 1985):

- frequencies from about 100 kHz to less than about 20 MHz, at which absorption in the trunk decreases rapidly with decreasing frequency, and significant absorption may occur in the neck and legs;
- frequencies in the range from about 20 MHz to 300 MHz, at which relatively high absorption can occur in the whole body, and to even higher values if partial body (e.g., head) resonances are considered;
- frequencies in the range from about 300 MHz to several GHz, at which significant local, non-uniform absorption occurs; and
- frequencies above about 10 GHz, at which energy absorption occurs primarily at the body surface.

In tissue, SAR is proportional to the square of the internal electric field strength. Average SAR and SAR distribution can be computed or estimated from laboratory measurements. Values of SAR depend on the following factors:

- the incident field parameters, i.e., the frequency, intensity, polarization, and source–object configuration (near- or far-field);
- the characteristics of the exposed body, i.e., its size and internal and external geometry, and the dielectric properties of the various tissues; and
- ground effects and reflector effects of other objects in the field near the exposed body.

When the long axis of the human body is parallel to the electric field vector, and under plane-wave exposure conditions (i.e., far-field exposure), whole-body SAR reaches maximal values. The amount of energy absorbed depends on a number of factors, including the size of the exposed body. "Standard Reference Man" (ICRP 1994), if not grounded, has a resonant absorption frequency close to 70 MHz. For taller individuals the resonant absorption frequency is somewhat lower, and for shorter adults, children, babies, and seated individuals it may exceed 100 MHz. The values of electric field reference levels are based on the frequency-dependence of human absorption; in grounded individuals, resonant frequencies are lower by a factor of about 2 (UNEP/WHO/IRPA 1993).

For some devices that operate at frequencies above 10 MHz (e.g., dielectric heaters, mobile telephones), human exposure can occur under near-field conditions. The frequency-dependence of energy absorption under these conditions is very different from that described for far-field conditions. Magnetic fields may dominate for certain devices, such as mobile telephones, under certain exposure conditions.

The usefulness of numerical modeling calculations, as well as measurements of induced body current and tissue field strength, for assessment of near-field exposures has been demonstrated for mobile telephones, walkie-talkies, broadcast towers, shipboard communication sources, and dielectric heaters (Kuster and Balzano 1992; Dimbylow and Mann 1994; Jokela et al. 1994; Gandhi 1995; Tofani et al. 1995). The importance of these studies lies in their having shown that near-field exposure can result in high local SAR (e.g., in the head, wrists, ankles) and that whole-body and local SAR are strongly dependent on the separation distance between the high-frequency source and the body. Finally, SAR data obtained by measurement are consistent with data obtained from numerical modeling calculations. Whole-body average SAR and local SAR are convenient quantities for comparing effects observed under various exposure conditions. A detailed discussion of SAR can be found elsewhere (UNEP/WHO/IRPA 1993).

At frequencies greater than about 10 GHz, the depth of penetration of the field into tissues is small, and SAR is not a good measure for assessing absorbed energy; the incident power density of the field (in W m^{-2}) is a more appropriate dosimetric quantity.

INDIRECT COUPLING MECHANISMS

There are two indirect coupling mechanisms:

- contact currents that result when the human body comes into contact with an object at a different electric potential (i.e., when either the body or the object is charged by an EMF); and
- coupling of EMF to medical devices worn by, or implanted in, an individual (not considered in this document).

The charging of a conducting object by EMF causes electric currents to pass through the human body in contact with that object (Tenforde and Kaune 1987; UNEP/WHO/IRPA 1993). The magnitude and spatial distribution of such currents depend on frequency, the size of the object, the size of the person, and the area of contact; transient discharges—sparks—can occur when an individual and a conducting object exposed to a strong field come into close proximity.

BIOLOGICAL BASIS FOR LIMITING EXPOSURE (UP TO 100 KHZ)

The following paragraphs provide a general review of relevant literature on the biological and health effects of electric and magnetic fields with frequency ranges up to 100 kHz, in which the major mechanism of interaction is induction of currents in tissues. For the frequency range >0 to 1 Hz, the biological basis for the basic restrictions and reference levels are provided in ICNIRP (1994). More detailed reviews are available elsewhere (NRPB 1991, 1993; UNEP/WHO/IRPA 1993; Blank 1995; NAS 1996; Polk and Postow 1996; Ueno 1996).

Direct effects of electric and magnetic fields

Epidemiological studies. There have been many reviews of epidemiological studies of cancer risk in relation to exposure to power-frequency fields (NRPB 1992, 1993, 1994b; ORAU 1992; Savitz 1993; Heath 1996; Stevens and Davis 1996; Tenforde 1996; NAS 1996). Similar reviews have been published on the risk of adverse reproductive outcomes associated with exposure to EMF (Chernoff et al. 1992; Brent et al. 1993; Shaw and Croen 1993; NAS 1996; Tenforde 1996).

Reproductive outcome. Epidemiological studies on pregnancy outcomes have provided no consistent evidence of adverse reproductive effects in women working with visual display units (VDUs) (Bergqvist 1993; Shaw and Croen 1993; NRPB 1994a; Tenforde 1996). For example, meta-analysis revealed no excess risk of spontaneous abortion or malformation in combined studies comparing pregnant women using VDUs with women not using VDUs (Shaw and Croen 1993). Two other studies concentrated on actual measurements of the electric and magnetic fields emitted by VDUs; one reported a suggestion of an association between ELF magnetic fields and miscarriage (Lindbohm et al. 1992), while the other found no such association (Schnorr et al. 1991). A prospective study that included large numbers of cases, had high participation rates, and detailed exposure assessment (Bracken et al. 1995) reported that neither birth weight nor intra-uterine growth rate was related to any ELF field exposure. Adverse outcomes were not associated with higher levels of exposure. Exposure measurements included current-carrying capacity of power lines outside homes, 7-d personal exposure measurements, 24-h measurements in the home, and self-reported use of electric blankets, heated water beds, and VDUs. Most currently available information fails to support an association between occupational exposure to VDUs and harmful reproductive effects (NRPB 1994a; Tenforde 1996).

Residential cancer studies. Considerable controversy surrounds the possibility of a link between exposure to ELF magnetic fields and an elevated risk of cancer. Several reports on this topic have appeared since Wertheimer and Leeper reported (1979) an association between childhood cancer mortality and proximity of homes to power distribution lines with what the researchers classified as *high current configuration*. The basic hypothesis that emerged from the original study was that the contribution to the ambient residential 50/60 Hz magnetic fields from external sources such as power lines could be linked to an increased risk of cancer in childhood.

To date there have been more than a dozen studies on childhood cancer and exposure to power-frequency magnetic fields in the home produced by nearby power lines. These studies estimated the magnetic field exposure from short term measurements or on the basis of distance between the home and power line and, in most cases, the configuration of the line; some studies also took the load of the line into account. The findings relating to leukemia are the most consistent. Out of 13 studies (Wertheimer and Leeper 1979; Fulton et al. 1980; Myers et al. 1985; Tomenius 1986; Savitz et al. 1988; Coleman et al. 1989; London et al. 1991; Feychting and Ahlbom 1993; Olsen et al. 1993; Verkasalo et al. 1993; Michaelis et al. 1997; Linet et al. 1997; Tynes and Haldorsen 1997), all but five reported relative risk estimates of between 1.5 and 3.0.

Both direct magnetic field measurements and estimates based on neighboring power lines are crude proxy measures for the exposure that took place at various times before cases of leukemia were diagnosed, and it is not clear which of the two methods provides the more valid estimate. Although results suggest that indeed the magnetic field may play a role in the association with leukemia risk, there is uncertainty because of small sample numbers and because of a correlation between the magnetic field and proximity to power lines (Feychting et al. 1996).

Little is known about the etiology of most types of childhood cancer, but several attempts to control for potential confounders such as socioeconomic status and air pollution from motor vehicle exhaust fumes have had little effect on results. Studies that have examined the use of electrical appliances (primarily electric blankets) in relation to cancer and other health problems have reported generally negative results (Preston-Martin et al. 1988; Verreault et al. 1990; Vena et al. 1991, 1994; Li et al. 1995). Only two case-control studies have evaluated use of appliances in relation to the risk of childhood leukemia. One was conducted in Denver (Savitz et al. 1990) and suggested a link with prenatal use of electric blankets; the other, carried out in Los Angeles (London et al. 1991), found an association between leukemia and children using hair dryers and watching monochrome television.

The fact that results for leukemia based on proximity of homes to power lines are relatively consistent led the U.S. National Academy of Sciences Committee to conclude that children living near power lines appear to be at increased risk of leukemia (NAS 1996). Because of small numbers, confidence intervals in the individual studies are wide; when taken together, however, the results are consistent, with a pooled relative risk of 1.5 (NAS 1996). In contrast, short-term measurements of magnetic field in some of the studies provided no evidence of an association between exposure to 50/60 Hz fields and the risk of leukemia or any other form of cancer in children. The Committee was not convinced that this increase in risk was explained by exposure to magnetic fields, since there was no apparent association when exposure was estimated from magnetic field meter readings in the homes of both leukemia cases and controls. It was suggested that confounding by some unknown risk factor for childhood leukemia, associated with residence in the vicinity of power lines, might be the explanation, but no likely candidates were postulated.

After the NAS committee completed its review, the results of a study performed in Norway were reported (Tynes and Haldorsen 1997). This study included 500 cases of all types of childhood cancer. Each individual's exposure was estimated by calculation of the magnetic field level produced in the residence by nearby transmission lines, estimated by averaging over an entire year. No association between leukemia risk and magnetic fields for the residence at time of diagnosis was observed. Distance from the power line, exposure during the first year of life, mothers' exposure at time of conception, and exposure higher than the median level of the controls showed no association with leukemia, brain cancer, or lymphoma. However, the number of exposed cases was small.

Also, a study performed in Germany has been reported after the completion of the NAS review (Michaelis et al. 1997). This was a case-control study on childhood leukemia based on 129 cases and 328 controls. Exposure assessment comprised measurements of the magnetic field over 24 h in the child's bedroom at the residence where the child had been living for the longest period before the date of diagnosis. An elevated relative risk of 3.2 was observed for >0.2 μT.

A large U.S. case-control study (638 cases and 620 controls) to test whether childhood acute lymphoblastic leukemia is associated with exposure to 60-Hz magnetic fields was published by Linet et al. (1997). Magnetic field exposures were determined using 24-h time-weighted average measurements in the bedroom and 30-s measurements in various other rooms. Measurements were taken in homes in which the child had lived for 70% of the 5 y prior to the year of diagnosis, or the corresponding period for the controls. Wire-codes were assessed for residentially stable case-control pairs in which both had not changed their residence during the years prior to diagnosis. The number of such pairs for which assessment could be made was 416. There was no indication of an association between wire-code category and leukemia. As for magnetic field measurements, the results are more intriguing. For the cut off point of 0.2 μT the unmatched and matched analyses gave relative risks of 1.2 and 1.5, respectively. For a cut off point of 0.3 μT, the unmatched relative risk estimate is 1.7 based on 45 exposed cases. Thus, the measurement results are suggestive of a positive association between magnetic fields and leukemia risk. This study is a major contribution in terms of its size, the number of subjects in high exposure categories, timing of measurements relative to the occurrence of the leukemia (usually within 24 mo after diagnosis), other measures used to obtain exposure data, and quality of analysis allowing for multiple potential confounders. Potential weaknesses include the procedure for control selection, the participation rates, and the methods used for statistical analysis of the data. The instruments used for measurements took no account of transient fields or higher order harmonics. The size of this study is such that its results, combined with those of other studies, would significantly weaken (though not necessarily invalidate) the previously observed association with wire code results.

Over the years there also has been substantial interest in whether there is an association between magnetic field exposure and childhood brain cancer, the second most frequent type of cancer found in children. Three recent studies completed after the NAS Committee's review fail to provide support for an association between brain cancer and children's exposure to magnetic fields, whether the source was power lines or electric blankets, or whether magnetic fields were estimated by calculations or by wire codes (Guénel et al. 1996; Preston-Martin et al. 1996a, b; Tynes and Haldorsen 1997).

Data on cancer in adults and residential magnetic field exposure are sparse (NAS 1996). The few studies published to date (Wertheimer and Leeper 1979; McDowall 1985; Seversen et al. 1988; Coleman et al. 1989; Schreiber et al. 1993; Feychting and Ahlbom 1994; Li et al. 1996; Verkasalo 1996; Verkasalo et al. 1996) all suffer to some extent from small numbers of exposed cases, and no conclusions can be drawn.

It is the view of the ICNIRP that the results from the epidemiological research on EMF field exposure and cancer, including childhood leukemia, are not strong enough in the absence of support from experimental research to form a scientific basis for setting exposure guidelines. This assessment is also in agreement with recent reviews (NRPB 1992, 1994b; NAS 1996; CRP 1997).

Occupational studies. A large number of epidemiological studies have been carried out to assess possible links between exposure to ELF fields and cancer risk among workers in electrical occupations. The first study of this type (Milham 1982) took advantage of a death certificate database that included both job titles and information on cancer mortality. As a crude method of assessing exposure, Milham classified job titles according to presumed magnetic field exposure and found an excess risk for leukemia among electrical workers. Subsequent studies (Savitz and Ahlbom 1994) made use of similar databases; the types of cancer for which elevated rates were noted varied across studies, particularly when cancer subtypes were characterized. Increased risks of various types of leukemia and nervous tissue tumors, and, in a few instances, of both male and female breast cancer, were reported (Demers et al. 1991; Matanoski et al. 1991; Tynes et al. 1992; Loomis et al. 1994). As well as producing somewhat inconsistent results, these studies suffered from very crude exposure assessment and from failure to control for confounding factors such as exposure to benzene solvent in the workplace.

Three recent studies have attempted to overcome some of the deficiencies in earlier work by measuring ELF field exposure at the workplace and by taking duration of work into consideration (Floderus et al. 1993; Thériault et al. 1994; Savitz and Loomis 1995). An elevated cancer risk among exposed individuals was observed, but the type of cancer of which this was true varied from study to study. Floderus et al. (1993) found a significant association with leukemia; an association was also noted by Thériault et al. (1994), but one that was weak and not significant, and no link was observed by Savitz and Loomis (1995). For subtypes of leukemia there was even greater inconsistency, but numbers in the analyses were small. For tumors of nervous tissue, Floderus et al. (1993) found an excess for glioblastoma (astrocytoma III–IV), while both Thériault et al. (1994) and Savitz and Loomis (1995) found only suggestive evidence for an increase in glioma (astrocytoma I–II). If there is truly a link between occupational exposure to magnetic fields and cancer, greater consistency and stronger associations would be expected of these recent studies based on more sophisticated exposure data.

Researchers have also investigated the possibility that ELF electric fields could be linked to cancer. The three utilities that participated in the Thériault et al. (1994) study of magnetic fields analyzed electric field data as well. Workers with leukemia at one of the utilities were reported to be more likely to have been exposed to electric fields than were control workers. In addition, the association was stronger in a group that had been exposed to high electric and magnetic fields combined (Miller et al. 1996). At the second utility, investigators reported no association between leukemia and higher cumulative exposure to workplace electric fields, but some of the analyses showed an association with brain cancer (Guénel et al. 1996). An association with colon cancer was also reported, yet in other studies of large populations of electric utility workers this type of cancer has not been found. At the third utility, no association between high electric fields and brain cancer or leukemia was observed, but this study was smaller and less likely to have detected small changes, if present (Baris et al. 1996).

An association between Alzheimer's disease and occupational exposure to magnetic fields has recently been suggested (Sobel and Davanipour 1996). However, this effect has not been confirmed.

Laboratory studies. The following paragraphs provide a summary and critical evaluation of laboratory studies on the biological effects of electric and magnetic fields with frequencies below 100 kHz. There are separate discussions on results obtained in studies of volunteers exposed under controlled conditions and in laboratory studies on cellular, tissue, and animal systems.

Volunteer studies. Exposure to a time-varying electric field can result in perception of the field as a result of the alternating electric charge induced on the body surface, which causes the body hairs to vibrate. Several studies have shown that the majority of people can perceive 50/60 Hz electric fields stronger than 20 kV m^{-1}, and that a small minority can perceive fields below 5 kV m^{-1} (UNEP/WHO/IRPA 1984; Tenforde 1991).

Small changes in cardiac function occurred in human volunteers exposed to combined 60-Hz electric and magnetic fields (9 kV m^{-1}, 20 μT) (Cook et al. 1992; Graham et al. 1994). Resting heart rate was slightly, but significantly, reduced (by 3–5 beats per minute) during or immediately after exposure. This response was absent on exposure to stronger (12 kV m^{-1}, 30 μT) or weaker (6 kV m^{-1}, 10 μT) fields and reduced if the subject was mentally alert. None of the subjects in these studies was able to detect the presence of the fields, and there were no other consistent results in a wide battery of sensory and perceptual tests.

No adverse physiological or psychological effects were observed in laboratory studies of people exposed to 50-Hz fields in the range 2–5 mT (Sander et al. 1982; Ruppe et al. 1995). There were no observed changes in blood chemistry, blood cell counts, blood gases, lactate levels, electrocardiogram, electroencephalogram, skin temperature, or circulating hormone levels in studies by Sander et al. (1982) and Graham et al. (1994). Recent studies on volunteers have also failed to show any effect of exposure to 60-Hz magnetic fields on the nocturnal melatonin level in blood (Graham et al. 1996, 1997; Selmaoui et al. 1996).

Sufficiently intense ELF magnetic fields can elicit peripheral nerve and muscle tissue stimulation directly, and short magnetic field pulses have been used clinically to stimulate nerves in the limbs in order to check the integrity of neural pathways. Peripheral nerve and muscle stimulation has also been reported in volunteers exposed to 1-kHz gradient magnetic fields in experimental magnetic resonance imaging systems. Threshold magnetic flux densities were several millitesla, and corresponding induced current densities in the peripheral tissues were about 1 A m^{-2} from pulsed fields produced by rapidly switched gradients. Time-varying magnetic fields that induce current densities above 1 A m^{-2} in tissue lead to neural excitation and are capable of producing irreversible biological effects such as cardiac fibrillation (Tenforde and Kaune 1987; Reilly 1989). In a study involving electromyographic recordings from the human arm (Polson et al. 1982), it was found that a pulsed field with dB/dt greater than 10^4 T s^{-1} was needed to stimulate the median nerve trunk. The duration of the magnetic stimulus has also been found to be an important parameter in stimulation of excitable tissues.

Thresholds lower than 100 mA m^{-2} can be derived from studies of visual and mental functions in human volunteers. Changes in response latency for complex reasoning tests have been reported in volunteers subjected to weak power-frequency electric currents passed through electrodes attached to the head and shoulders; current densities were estimated to lie between 10 and 40 mA m^{-2} (Stollery 1986, 1987). Finally, many studies have reported that volunteers experienced faint flickering visual sensations, known as magnetic phosphenes, during exposure to ELF magnetic fields above 3–5 mT (Silny 1986). These visual effects can also be induced by the direct application of weak electric currents to the head. At 20 Hz, current densities of about 10 mA m^{-2} in the retina have been estimated as the threshold for induction of phosphenes, which is above the typical endogenous current densities in electrically excitable tissues. Higher thresholds have been observed for both lower and higher frequencies (Lövsund et al. 1980; Tenforde 1990).

Studies have been conducted at 50 Hz on visually evoked potentials that exhibited thresholds for effects at flux densities of 60 mT (Silny 1986). Consistent with this result, no effects on visually evoked potentials were obtained by either Sander et al. (1982), using a 50-Hz, 5-mT field, or Graham et al. (1994), using combined 60-Hz electric and magnetic fields up to 12 kV m^{-1} and 30 μT, respectively.

Cellular and animal studies. Despite the large number of studies undertaken to detect biological effects of ELF electric and magnetic fields, few systematic studies have defined the threshold field characteristics that produce significant perturbations of biological functions. It is well established that induced electric current can stimulate nerve and muscle tissue directly once the induced current density exceeds threshold values (UNEP/WHO/IRPA 1987; Bernhardt 1992; Tenforde 1996). Current densities that are unable to stimulate excitable tissues directly may nevertheless affect ongoing electrical activity and influence neuronal excitability. The activity of the central nervous system is known to be sensitive to the endogenous electric fields generated by the action of adjacent nerve cells, at levels below those required for direct stimulation.

Many studies have suggested that the transduction of weak electrical signals in the ELF range involves interactions with the cell membrane, leading to cytoplasmic biochemical responses that in turn involve changes in cellular functional and proliferative states. From simple models of the behavior of single cells in weak fields it has been calculated that an electrical signal in the extracellular field must be greater than approximately 10–100 mV m^{-1} (corresponding to an induced current density of about 2–20 mA m^{-2}) in order to exceed the level of endogenous physical and biological noise in cellular membranes (Astumian et al. 1995). Existing evidence also suggests that several structural and functional properties of membranes may be altered in response to induced ELF fields at or below 100 mV m^{-1} (Sienkiewicz et al. 1991; Tenforde 1993). Neuroendocrine alterations (e.g., suppression of nocturnal melatonin synthesis) have been reported in response to induced electrical fields of 10 mV m^{-1} or less, corresponding to induced current densities of approximately 2 mA m^{-2} or less (Tenforde 1991, 1996). However, there is no clear evidence that these biological interactions of low-frequency fields lead to adverse health effects.

Induced electric fields and currents at levels exceeding those of endogenous bioelectric signals present in tissue have been shown to cause a number of physiological effects that increase in severity as the induced current density is increased (Bernhardt 1979; Tenforde 1996). In the current density range 10–100 mA m^{-2}, tissue effects and changes in brain cognitive functions have been reported (NRPB 1992; NAS 1996). When induced current density exceeds 100 to several hundred mA m^{-2} for frequencies between about 10 Hz and 1 kHz, thresholds for neuronal and neuromuscular stimulation are exceeded. The threshold current densities increase progressively at frequencies below several hertz and above 1 kHz. Finally, at extremely high current densities, exceeding 1 A m^{-2}, severe and potentially life-threatening effects such as cardiac extrasystoles, ventricular fibrillation, muscular tetanus, and respiratory failure may occur. The severity and the probability of irreversibility of tissue effects becomes greater with chronic exposure to induced current densities above the level 10 to 100 mA m^{-2}. It therefore seems appropriate to limit human exposure to fields that induce current densities no greater than 10 mA m^{-2} in the head, neck, and trunk at frequencies of a few hertz up to 1 kHz.

It has been postulated that oscillatory magnetomechanical forces and torques on biogenic magnetite particles in brain tissue could provide a mechanism for the transduction of signals from ELF magnetic fields. Kirschvink et al. (1992b) proposed a model in which ELF magnetic forces on magnetite particles are visualized as producing the opening and closing of pressure-sensitive ion channels in membranes. However, one difficulty with this model is the sparsity of magnetite particles relative to the number of cells in brain tissue. For example, human brain tissue has been reported to contain a few million magnetite particles per gram, distributed in 10^5 discrete clusters of 5–10 particles (Kirschvink et al. 1992a). The number of cells in brain tissue thus exceeds the number of magnetite particles by a factor of about 100, and it is difficult to envisage how oscillating magnetomechanical interactions of an ELF field with magnetite crystals could affect a significant number of pressure-sensitive ion channels in the brain. Further studies are clearly needed to reveal the biological role of magnetite and the possible mechanisms through which this mineral could play a role in the transduction of ELF magnetic signals.

An important issue in assessing the effects of electromagnetic fields is the possibility of teratogenic and developmental effects. On the basis of published scientific evidence, it is unlikely that low-frequency fields have adverse effects on the embryonic and postnatal development of mammalian species (Chernoff et al. 1992; Brent et al. 1993; Tenforde 1996). Moreover, currently available evidence indicates that somatic mutations and genetic effects are unlikely to result from exposure to electric and magnetic fields with frequencies below 100 kHz (Cridland 1993; Sienkiewicz et al. 1993).

There are numerous reports in the literature on the *in-vitro* effects of ELF fields on cell membrane properties (ion transport and interaction of mitogens with cell surface receptors) and changes in cellular functions and growth properties (e.g., increased proliferation and alterations in metabolism, gene expression, protein biosynthesis, and enzyme activities) (Cridland 1993; Sienkiewicz et al. 1993; Tenforde 1991, 1992, 1993, 1996). Considerable attention has focused on low-frequency field effects on Ca^{++} transport across cell membranes and the intracellular concentration of this ion (Walleczek and Liburdy 1990; Liburdy 1992; Walleczek 1992), messenger RNA and protein synthesis patterns (Goodman et al. 1983; Goodman and Henderson 1988, 1991; Greene et al. 1991; Phillips et al. 1992), and the activity of enzymes such as ornithine decarboxylase (ODC) that are related to cell proliferation and tumor promotion (Byus et al. 1987, 1988; Litovitz et al. 1991, 1993). However, before these observations can be used for defining exposure limits, it is essential to establish both their reproducibility and their relevance to cancer or other adverse health outcomes. This point is underscored by the fact that there have been difficulties in replicating some of the key observations of field effects on gene expression and protein synthesis (Lacy-Hulbert et al. 1995; Saffer and Thurston 1995). The authors of these replication studies identified several deficiencies in the earlier studies, including poor temperature control, lack of appropriate internal control samples, and the use of low-resolution techniques for analyzing the production of messenger RNA transcripts. The transient increase in ODC activity reported in response to field exposure is small in magnitude and not associated with *de novo* synthesis of the enzyme (unlike chemical tumor promoters such as phorbol esters) (Byus et al. 1988). Studies on ODC have mostly involved cellular preparations; more studies are needed to show whether there are effects on ODC *in vivo*, although there is one report suggesting effects on ODC in a rat mammary tumor promotion assay (Mevissen et al. 1995).

There is no evidence that ELF fields alter the structure of DNA and chromatin, and no resultant mutational and neoplastic transformation effects are expected. This is supported by results of laboratory studies designed to detect DNA and chromosomal damage, mutational events, and increased transformation frequency in response to ELF field exposure (NRPB 1992; Murphy et al. 1993; McCann et al. 1993; Tenforde 1996). The lack of effects on chromosome structure suggests that ELF fields, if they have any effect on the process of carcinogenesis, are more likely to act as promoters than initiators, enhancing the proliferation of genetically altered cells rather than causing the initial lesion in DNA or chromatin. An influence on tumor development could be mediated through epigenetic effects of these fields, such as alterations in cell signalling pathways or gene expression. The focus of recent studies has therefore been on detecting possible effects of ELF fields on the promotion and progression phases of tumor development following initiation by a chemical carcinogen.

Studies on *in-vitro* tumor cell growth and the development of transplanted tumors in rodents have provided no strong evidence for possible carcinogenic effects of exposure to ELF fields (Tenforde 1996). Several studies of more direct relevance to human cancer have involved *in-vivo* tests for tumor-promoting activity of ELF magnetic fields on skin, liver, brain, and mammary tumors in rodents. Three studies of skin tumor promotion (McLean et al. 1991; Rannug et al. 1993a, 1994) failed to show any effect of either continuous or intermittent exposure to power-frequency magnetic fields in promoting chemically induced tumors. At a 60-Hz field strength of 2 mT, a co-promoting effect with a phorbol ester was reported for mouse skin tumor development in the initial stages of the experiment, but the statistical significance of this was lost by completion of the study in week 23 (Stuchly et al. 1992). Previous studies by the same investigators had shown that 60-Hz, 2-mT field exposure did not promote the growth of DMBA-initiated skin cells (McLean et al. 1991).

Experiments on the development of transformed liver foci initiated by a chemical carcinogen and promoted by phorbol ester in partially hepatectomized rats revealed no promotion or co-promotion effect of exposure to 50-Hz fields ranging in strength from 0.5 to 50 μT (Rannug et al. 1993b, c).

Studies on mammary cancer development in rodents treated with a chemical initiator have suggested a cancer-promoting effect of exposure to power-frequency magnetic fields in the range 0.01–30 mT (Beniashvili et al. 1991; Löscher et al. 1993; Mevissen et al. 1993, 1995; Baum et al. 1995; Löscher and Mevissen 1995). These observations of increased tumor incidence in rats exposed to magnetic fields have been hypothesized to be related to field-induced suppression of pineal melatonin and a resulting elevation in steroid hormone levels and breast cancer risk (Stevens 1987; Stevens et al. 1992). However, replication efforts by independent laboratories are needed before conclusions can be drawn regarding the implications of these findings for a promoting effect of ELF magnetic fields on mammary tumors. It should also be noted that recent studies have found no evidence for a significant effect of exposure to ELF magnetic fields on melatonin levels in humans (Graham et al. 1996, 1997; Selmaoui et al. 1996).

Indirect effects of electric and magnetic fields

Indirect effects of electromagnetic fields may result from physical contact (e.g., touching or brushing against) between a person and an object, such as a metallic structure in the field, at a different electric potential. The result of such contact is the flow of electric charge (contact current) that may have accumulated on the object or on the body of the person. In the frequency range up to approximately 100 kHz, the flow of electric current from an object in the field to the body of the individual may result in the stimulation of muscles and/or peripheral nerves. With increasing levels of current this may be manifested as perception, pain from electric shock and/or burn, inability to release the object, difficulty in breathing and, at very high currents, cardiac ventricular fibrillation (Tenforde and Kaune 1987). Threshold values for these effects are frequency-dependent, with the lowest threshold occurring at frequencies between 10 and 100 Hz. Thresholds for peripheral nerve responses remain low for frequencies up to several kHz. Appropriate engineering and/or administrative controls, and even the wearing of personal protective clothing, can prevent these problems from occurring.

Spark discharges can occur when an individual comes into very close proximity with an object at a different electric potential, without actually touching it (Tenforde and Kaune 1987; UNEP/WHO/IRPA 1993). When a group of volunteers, who were electrically insulated from the ground, each held a finger tip close to a grounded object, the threshold for perception of spark discharges was as low as 0.6–1.5 kV m^{-1} in 10% of cases. The threshold field level reported as causing annoyance under these exposure conditions is about 2.0–3.5 kV m^{-1}. Large contact currents can result in muscle contraction. In male volunteers, the 50th percentile threshold for being unable to release a charged conductor has been reported as 9 mA at 50/60 Hz, 16 mA at 1 kHz, about 50 mA at 10 kHz, and about 130 mA at 100 kHz (UNEP/WHO/IRPA 1993).

The threshold currents for various indirect effects of fields with frequencies up to 100 kHz are summarized in Table 2 (UNEP/WHO/IRPA 1993).

Table 2. Ranges of threshold currents for indirect effects, including children, women, and men.

Indirect effect	Threshold current (mA) at frequency: 50/60 Hz	1 kHz	100 kHz
Touch perception	0.2–0.4	0.4–0.8	25–40
Pain on finger contact	0.9–1.8	1.6–3.3	33–55
Painful shock/let-go threshold	8–16	12–24	112–224
Severe shock/breathing difficulty	12–23	21–41	160–320

Summary of biological effects and epidemiological studies (up to 100 kHz)

With the possible exception of mammary tumors, there is little evidence from laboratory studies that power-frequency magnetic fields have a tumor-promoting effect. Although further animal studies are needed to clarify the possible effects of ELF fields on signals produced in cells and on endocrine regulation—both of which could influence the development of tumors by promoting the proliferation of initiated cells—it can only be concluded that there is currently no convincing evidence for carcinogenic effects of these fields and that these data cannot be used as a basis for developing exposure guidelines.

Laboratory studies on cellular and animal systems have found no established effects of low-frequency fields that are indicative of adverse health effects when induced current density is at or below 10 mA m^{-2}. At higher levels of induced current density (10–100 mA m^{-2}), more significant tissue effects have been consistently observed, such as functional changes in the nervous system and other tissue effects (Tenforde 1996).

Data on cancer risk associated with exposure to ELF fields among individuals living close to power lines are apparently consistent in indicating a slightly higher risk of leukemia among children, although more recent studies question the previously observed weak association. The studies do not, however, indicate a similarly elevated risk of any other type of childhood cancer or of any form of adult cancer. The basis for the hypothetical link between childhood leukemia and residence in close proximity to power lines is unknown; if the link is not related to the ELF electric and magnetic fields generated by the power lines, then unknown risk factors for leukemia would have to be linked to power lines in some undetermined manner. In the absence of support from laboratory studies, the epidemiological data are insufficient to allow an exposure guideline to be established.

There have been reports of an increased risk of certain types of cancer, such as leukemia, nervous tissue tumors, and, to a limited extent, breast cancer, among electrical workers. In most studies, job titles were used to classify subjects according to presumed levels of magnetic field exposure. A few more recent studies, however, have used more sophisticated methods of exposure assessment; overall, these studies suggested an increased risk of leukemia or brain tumors but were largely inconsistent with regard to the type of cancer for which risk is increased. The data are insufficient to provide a basis for ELF field exposure guidelines. In a large number of epidemiological studies, no consistent evidence of adverse reproductive effects have been provided.

Measurement of biological responses in laboratory studies and in volunteers has provided little indication of adverse effects of low-frequency fields at levels to which people are commonly exposed. A threshold current density of 10 mA m^{-2} at frequencies up to 1 kHz has been estimated for minor effects on nervous system functions. Among volunteers, the most consistent effects of exposure are the appearance of visual phosphenes and a minor reduction in heart rate during or immediately after exposure to ELF fields, but there is no evidence that these transient effects are associated with any long-term health risk. A reduction in nocturnal pineal melatonin synthesis has been observed in several rodent species following exposure to weak ELF electric and magnetic fields, but no consistent effect has been reported in humans exposed to ELF fields under controlled conditions. Studies involving exposures to 60-Hz magnetic fields up to 20 μT have not reported reliable effects on melatonin levels in blood.

BIOLOGICAL BASIS FOR LIMITING EXPOSURE (100 kHz–300 GHz)

The following paragraphs provide a general review of relevant literature on the biological effects and potential health effects of electromagnetic fields with frequencies of 100 kHz to 300 GHz. More detailed reviews can be found elsewhere (NRPB 1991; UNEP/WHO/IRPA 1993; McKinlay et al. 1996; Polk and Postow 1996; Repacholi 1998).

Direct effects of electromagnetic fields

Epidemiological studies. Only a limited number of studies have been carried out on reproductive effects and cancer risk in individuals exposed to microwave radiation. A summary of the literature was published by UNEP/WHO/IRPA (1993).

Reproductive outcomes. Two extensive studies on women treated with microwave diathermy to relieve the pain of uterine contractions during labor found no evidence for adverse effects on the fetus (Daels 1973, 1976). However, seven studies on pregnancy outcomes among workers occupationally exposed to microwave radiation and on birth defects among their offspring produced both positive and negative results. In some of the larger epidemiological studies of female plastic welders and physiotherapists working with shortwave diathermy devices, there were no statistically significant effects on rates of abortion or fetal malformation (Källen et al. 1982). By contrast, other studies on similar populations of female workers found an increased risk of miscarriage and birth defects (Larsen et al. 1991; Ouellet-Hellstrom and Stewart 1993). A study of male radar workers found no association between microwave exposure and the risk of Down's syndrome in their offspring (Cohen et al. 1977).

Overall, the studies on reproductive outcomes and microwave exposure suffer from very poor assessment of exposure and, in many cases, small numbers of subjects. Despite the generally negative results of these studies, it will be difficult to draw firm conclusions on reproductive risk without further epidemiological data on highly exposed individuals and more precise exposure assessment.

Cancer studies. Studies on cancer risk and microwave exposure are few and generally lack quantitative exposure assessment. Two epidemiological studies of radar workers in the aircraft industry and in the U.S. armed forces found no evidence of increased morbidity or mortality from any cause (Barron and Baraff 1958; Robinette et al. 1980; UNEP/WHO/IRPA 1993). Similar results were obtained by Lillienfeld et al. (1978) in a study of employees in the U.S. embassy in Moscow, who were chronically exposed to low-level microwave radiation. Selvin et al. (1992) reported no increase in cancer risk among children chronically exposed to radiation from a large microwave transmitter near their homes. More recent studies have failed to show significant increases in nervous tissue tumors among workers and military personnel exposed to microwave fields (Beall et al. 1996; Grayson 1996). Moreover, no excess total mortality was apparent among users of mobile telephones (Rothman et al. 1996a, b), but it is still too early to observe an effect on cancer incidence or mortality.

There has been a report of increased cancer risk among military personnel (Szmigielski et al. 1988), but the results of the study are difficult to interpret because neither the size of the population nor the exposure levels are clearly stated. In a later study, Szmigielski (1996) found increased rates of leukemia and lymphoma among military personnel exposed to EMF fields, but the assessment of EMF exposure was not well defined. A few recent studies of populations living near EMF transmitters have suggested a local increase in leukemia incidence (Hocking et al. 1996; Dolk et at. 1997a, b), but the results are inconclusive. Overall, the results of the small number of epidemiological studies published provide only limited information on cancer risk.

Laboratory studies. The following paragraphs provide a summary and critical evaluation of laboratory studies on the biological effects of electromagnetic fields with frequencies in the range 100 kHz–300 GHz. There are separate discussions on results of studies of volunteers exposed under controlled conditions and of laboratory studies on cellular, tissue, and animal systems.

Volunteer studies. Studies by Chatterjee et al. (1986) demonstrated that, as the frequency increases from approximately 100 kHz to 10 MHz, the dominant effect of exposure to a high-intensity electromagnetic field changes from nerve and muscle stimulation to heating. At 100 kHz the primary sensation was one of nerve tingling, while at 10 MHz it was one of warmth on the skin. In this frequency range, therefore, basic health protection criteria should be such as to avoid stimulation of excitable tissues and heating effects. At frequencies from 10 MHz to 300 GHz, heating is the major effect of absorption of electromagnetic energy, and temperature rises of more than 1–2 °C can have adverse health effects such as heat exhaustion and heat stroke (ACGIH 1996). Studies on workers in thermally stressful environments have shown worsening performance of simple tasks as body temperature rises to a level approaching physiological heat stress (Ramsey and Kwon 1988).

A sensation of warmth has been reported by volunteers experiencing high-frequency current of about 100–200 mA through a limb. The resulting SAR value is unlikely to produce a localized temperature increment of more than 1°C in the limbs (Chatterjee et al. 1986; Chen and Gandhi 1988; Hoque and Gandhi 1988), which has been suggested as the upper limit of temperature increase that has no detrimental health effects (UNEP/WHO/IRPA 1993). Data on volunteers reported by Gandhi et al. (1986) for frequencies up to 50 MHz and by Tofani et al. (1995) for frequencies up to 110 MHz (the upper limit of the FM broadcast band) support a reference level for limb current of 100 mA to avoid excessive heating effects (Dimbylow 1997).

There have been several studies of thermoregulatory responses of resting volunteers exposed to EMF in magnetic resonance imaging systems (Shellock and Crues 1987; Magin et al. 1992). In general, these have demonstrated that exposure for up to 30 min, under conditions in which whole-body SAR was less than 4 W kg^{-1}, caused an increase in the body core temperature of less than 1°C.

Cellular and animal studies. There are numerous reports on the behavioral and physiological responses of laboratory animals, including rodents, dogs, and nonhuman primates, to thermal interactions of EMF at frequencies above 10 MHz. Thermosensitivity and thermoregulatory responses are associated both with the hypothalamus and with thermal receptors located in the skin and in internal parts of the body. Afferent signals reflecting temperature change converge in the central nervous system and modify the activity of the major neuroendocrine control systems, triggering the physiological and behavioral responses necessary for the maintenance of homeostasis.

Exposure of laboratory animals to EMF producing absorption in excess of approximately 4 W kg^{-1} has revealed a characteristic pattern of thermoregulatory response in which body temperature initially rises and then stabilizes following the activation of thermoregulatory mechanisms (Michaelson 1983). The early phase of this response is accompanied by an increase in blood volume due to movement of fluid from the extracellular space into the circulation and by increases in heart rate and intraventricular blood pressure. These cardiodynamic changes reflect thermoregulatory responses that facilitate the conduction of heat to the body surface. Prolonged exposure of animals to levels of microwave radiation that raise the body temperature ultimately lead to failure of these thermoregulatory mechanisms.

Several studies with rodents and monkeys have also demonstrated a behavioral component of thermoregulatory responses. Decreased task performance by rats and monkeys has been observed at SAR values in the range 1–3 W kg^{-1} (Stern et al. 1979; Adair and Adams 1980; de Lorge and Ezell 1980; D'Andrea et al. 1986). In monkeys, altered thermoregulatory behavior starts when the temperature in the hypothalamic region rises by as little as 0.2–0.3°C (Adair et al. 1984). The hypothalamus is considered to be the control center for normal thermoregulatory processes, and its activity can be modified by a small local temperature increase under conditions in which rectal temperature remains constant.

At levels of absorbed electromagnetic energy that cause body temperature rises in excess of 1–2°C, a large number of physiological effects have been characterized in studies with cellular and animal systems (Michaelson and Elson 1996). These effects include alterations in neural and neuromuscular functions; increased blood-brain barrier permeability; ocular impairment (lens opacities and corneal abnormalities); stress-associated changes in the immune system; hematological changes; reproductive changes (e.g., reduced sperm production); teratogenicity; and changes in cell morphology, water and electrolyte content, and membrane functions.

Under conditions of partial-body exposure to intense EMF, significant thermal damage can occur in sensitive tissues such as the eye and the testis. Microwave exposure of 2–3 h duration has produced cataracts in rabbits' eyes at SAR values from 100–140 W kg^{-1}, which produced lenticular temperatures of 41–43°C (Guy et al. 1975). No cataracts were observed in monkeys exposed to microwave fields of similar or higher intensities, possibly because of different energy absorption patterns in the eyes of monkeys from those in rabbits. At very high frequencies (10–300 GHz), absorption of electromagnetic energy is confined largely to the epidermal layers of the skin, subcutaneous tissues, and the outer part of the eye. At the higher end of the frequency range, absorption is increasingly superficial. Ocular damage at these frequencies can be avoided if the microwave power density is less than 50 W m^{-2} (Sliney and Wolbarsht 1980; UNEP/WHO/IRPA 1993).

There has been considerable recent interest in the possible carcinogenic effects of exposure to microwave fields with frequencies in the range of widely used communications systems, including hand-held mobile telephones and base transmitters. Research findings in this area have been summarized by ICNIRP (1996). Briefly, there are many reports suggesting that microwave fields are not mutagenic, and exposure to these fields is therefore unlikely to initiate carcinogenesis (NRPB 1992; Cridland 1993; UNEP/WHO/IRPA 1993). By contrast, some recent reports suggest that exposure of rodents to microwave fields at SAR levels of the order of 1 W kg^{-1} may produce strand breaks in the DNA of testis and brain tissues (Sarkar et al. 1994; Lai and Singh 1995, 1996), although both ICNIRP (1996) and Williams (1996) pointed out methodological deficiencies that could have significantly influenced these results.

In a large study of rats exposed to microwaves for up to 25 mo, an excess of primary malignancies was noted in exposed rats relative to controls (Chou et al. 1992). However, the incidence of benign tumors did not differ between the groups, and no specific type of tumor was more prevalent in the exposed group than in stock rats of the same strain maintained under similar specific-pathogen-free conditions. Taken as a whole, the results of this study cannot be interpreted as indicating a tumor-initiating effect of microwave fields.

Several studies have examined the effects of microwave exposure on the development of pre-initiated tumor cells. Szmigielski et al. (1982) noted an enhanced growth rate of transplanted lung sarcoma cells in rats exposed to microwaves at high power densities. It is possible that this resulted from a weakening of the host immune defense in response to thermal stress from the microwave exposure. Recent studies using athermal levels of microwave irradiation have found no effects on the development of melanoma in mice or of brain glioma in rats (Santini et al. 1988; Salford et al. 1993).

Repacholi et al. (1997) have reported that exposure of 100 female, *Eμ-pim1* transgenic mice to 900-MHz fields, pulsed at 217 Hz with pulse widths of 0.6 μs for up to 18 mo, produced a doubling in lymphoma incidence compared with 101 controls. Because the mice were free to roam in their cages, the variation in SAR was wide (0.01–4.2 W kg^{-1}). Given that the resting metabolic rate of these mice is 7–15 W kg^{-1}, only the upper end of the exposure range may have produced some slight heating. Thus, it appears that this study suggests a non-thermal mechanism may be acting, which needs to be investigated further. However, before any assumptions can be made about health risk, a number of questions need to be addressed. The study needs to be replicated, restraining the animals to decrease the SAR exposure variation and to determine whether there is a dose response. Further study is needed to determine whether the results can be found in other animal models in order to be able to generalize the results to humans. It is also essential to assess whether results found in transgenic animals are applicable to humans.

Special considerations for pulsed and amplitude-modulated waveforms

Compared with continuous-wave (CW) radiation, pulsed microwave fields with the same average rate of energy deposition in tissues are generally more effective in producing a biological response, especially when there is a well-defined threshold that must be exceeded to elicit the effect (ICNIRP 1996). The "microwave hearing" effect is a well known example of this (Frey 1961; Frey and Messenger 1973; Lin 1978): people with normal hearing can perceive pulse-modulated fields with frequencies between about 200 MHz and 6.5 GHz. The auditory sensation has been variously described as a buzzing, clicking, or popping sound, depending on the modulation characteristics of the field. The microwave hearing effects have been attributed to a thermoelastic interaction in the auditory cortex of the brain, with a threshold for perception of about 100–400 mJ m^{-2} for pulses of duration less than 30 μs at 2.45 GHz (corresponding to an SA of 4–16 mJ kg^{-1}). Repeated or prolonged exposure to microwave auditory effects may be stressful and potentially harmful.

Some reports suggest that retina, iris, and corneal endothelium of the primate eye are sensitive to low levels of pulsed microwave radiation (Kues et al. 1985; UNEP/WHO/IRPA 1993). Degenerative changes in light-sensitive cells of the retina were reported for absorbed energy levels as low as 26 mJ kg^{-1}. After administration of timolol maleate, which is used in the treatment of glaucoma, the threshold for retinal damage by pulsed fields dropped to 2.6 mJ kg^{-1}. However, an attempt in an independent laboratory to partially replicate these findings for CW fields (i.e., not pulsed) was unsuccessful (Kamimura et al. 1994), and it is therefore impossible at present to assess the potential health implications of the initial findings of Kues et al. (1985).

Exposure to intense pulsed microwave fields has been reported to suppress the startle response in conscious mice and to evoke body movements (NRPB 1991; Sienkiewicz et al. 1993; UNEP/WHO/IRPA 1993). The threshold specific energy absorption level at midbrain that evoked body movements was 200 J kg^{-1} for 10 μs pulses. The mechanism for these effects of pulsed microwaves remains to be determined but is believed to be related to the microwave hearing phenomenon. The auditory thresholds for rodents are about an order of magnitude lower than for humans, that is 1–2 mJ kg^{-1} for pulses <30 μs in duration. Pulses of this magnitude have also been reported to affect neurotransmitter metabolism and the concentration of the neural receptors involved in stress and anxiety responses in different regions of the rat brain.

The issue of athermal interactions of high-frequency EMF has centered largely on reports of biological effects of amplitude modulated (AM) fields under *in-vitro* conditions at SAR values well below those that produce measurable tissue heating. Initial studies in two independent laboratories led to reports that VHF fields with amplitude modulation at extremely low frequencies (6–20 Hz) produced a small, but statistically significant, release of Ca^{++} from the surfaces of chick brain cells (Bawin et al. 1975; Blackman et al. 1979). A subsequent attempt to replicate these findings, using the same type of AM field, was unsuccessful (Albert et al. 1987). A number of other studies of the effects of AM fields on Ca^{++} homeostasis have produced both positive and negative results. For example, effects of AM fields on Ca^{++} binding to cell surfaces have been observed with neuroblastoma cells, pancreatic cells, cardiac tissue, and cat brain cells, but not with cultured rat nerve cells, chick skeletal muscle, or rat brain cells (Postow and Swicord 1996).

Amplitude-modulated fields have also been reported to alter brain electrical activity (Bawin et al. 1974), inhibit T-lymphocyte cytotoxic activity (Lyle et al. 1983), decrease the activities of non-cyclic-AMP-dependent kinase in lymphocytes (Byus et al. 1984), and cause a transient increase in the cytoplasmic activity of ornithine decarboxylase, an essential enzyme for cell proliferation (Byus et al. 1988; Litovitz et al. 1992). In contrast, no effects have been observed on a wide variety of other cellular systems and functional end-points, including lymphocyte capping, neoplastic cell transformation, and various membrane electrical and enzymatic properties (Postow and Swicord 1996). Of particular relevance to the potential carcinogenic effects of pulsed fields is the observation by Balcer-Kubiczek and Harrison (1991) that neoplastic transformation was accelerated in C3H/10T1/2 cells exposed to 2,450-MHz microwaves that were pulse-modulated at 120 Hz. The effect was dependent on field strength but occurred only when a chemical tumor-promoter, TPA, was present in the cell culture medium. This finding suggests that pulsed microwaves may exert co-carcinogenic effects in combination with a chemical agent that increases the rate of proliferation of transformed cells. To date, there have been no attempts to replicate this finding, and its implication for human health effects is unclear.

Interpretation of several observed biological effects of AM electromagnetic fields is further complicated by the apparent existence of "windows" of response in both the power density and frequency domains. There are no accepted models that adequately explain this phenomenon, which challenges the traditional concept of a monotonic relationship between the field intensity and the severity of the resulting biological effects.

Overall, the literature on athermal effects of AM electromagnetic fields is so complex, the validity of reported effects so poorly established, and the relevance of the effects to human health is so uncertain, that it is impossible to use this body of information as a basis for setting limits on human exposure to these fields.

Indirect effects of electromagnetic fields

In the frequency range of about 100 kHz–110 MHz, shocks and burns can result either from an individual touching an ungrounded metal object that has acquired a charge in a field or from contact between a charged individual and a grounded metal object. It should be noted that the upper frequency for contact current (110 MHz) is imposed by a lack of data on higher frequencies rather than by the absence of effects. However, 110 MHz is the upper frequency limit of the FM broadcast band. Threshold currents that result in biological effects ranging in severity from perception to pain have been measured in controlled experiments on volunteers (Chatterjee et al. 1986; Tenforde and Kaune 1987; Bernhardt 1988); these are summarized in Table 3. In general, it has been shown that the threshold currents that produce perception and pain vary little over the frequency range 100 kHz–1 MHz and are unlikely to vary significantly over the frequency range up to about 110 MHz. As noted earlier for lower frequencies, significant variations between the sensitivities of men, women, and children also exist for higher frequency fields. The data in Table 3 represent the range of 50th percentile values for people of different sizes and different levels of sensitivity to contact currents.

Table 3. Ranges of threshold currents for indirect effects, including children, women, and men.

Indirect effect	Threshold current (mA) at frequency: 100 kHz	1 MHz
Touch perception	25–40	25–40
Pain on finger contact	33–55	28–50
Painful shock/let-go threshold	112–224	Not determined
Severe shock/breathing difficulty	160–320	Not determined

Summary of biological effects and epidemiological studies (100 kHz–300 GHz)

Available experimental evidence indicates that the exposure of resting humans for approximately 30 min to EMF producing a whole-body SAR of between 1 and 4 W kg^{-1} results in a body temperature increase of less than 1 °C. Animal data indicate a threshold for behavioral responses in the same SAR range. Exposure to more intense fields, producing SAR values in excess of 4 W kg^{-1}, can overwhelm the thermoregulatory capacity of the body and produce harmful levels of tissue heating. Many laboratory studies with rodent and non-human primate models have demonstrated the broad range of tissue damage resulting from either partial-body or whole-body heating producing temperature rises in excess of 1–2°C. The sensitivity of various types of tissue to thermal damage varies widely, but the threshold for irreversible effects in even the most sensitive tissues is greater than 4 W kg^{-1} under normal environmental conditions. These data form the basis for an occupational exposure restriction of 0.4 W kg^{-1}, which provides a large margin of safety for other limiting conditions such as high ambient temperature, humidity, or level of physical activity.

Both laboratory data and the results of limited human studies (Michaelson and Elson 1996) make it clear that thermally stressful environments and the use of drugs or alcohol can compromise the thermoregulatory capacity of the body. Under these conditions, safety factors should be introduced to provide adequate protection for exposed individuals.

Data on human responses to high-frequency EMF that produce detectable heating have been obtained from controlled exposure of volunteers and from epidemiological studies on workers exposed to sources such as radar, medical diathermy equipment, and heat sealers. They are fully supportive of the conclusions drawn from laboratory work, that adverse biological effects can be caused by temperature rises in tissue that exceed 1°C. Epidemiological studies on exposed workers and the general public have shown no major health effects associated with typical exposure environments. Although there are deficiencies in the epidemiological work, such as poor exposure assessment, the studies have yielded no convincing evidence that typical exposure levels lead to adverse reproductive outcomes or an increased cancer risk in exposed individuals. This is consistent with the results of laboratory research on cellular and animal models, which have demonstrated neither teratogenic nor carcinogenic effects of exposure to athermal levels of high-frequency EMF.

Exposure to pulsed EMF of sufficient intensity leads to certain predictable effects such as the microwave hearing phenomenon and various behavioral responses. Epidemiological studies on exposed workers and the general public have provided limited information and failed to demonstrate any health effects. Reports of severe retinal damage have been challenged following unsuccessful attempts to replicate the findings.

A large number of studies of the biological effects of amplitude-modulated EMF, mostly conducted with low levels of exposure, have yielded both positive and negative results. Thorough analysis of these studies reveals that the effects of AM fields vary widely with the exposure parameters, the types of cells and tissues involved, and the biological end-points that are examined. In general, the effects of exposure of biological systems to athermal levels of amplitude-modulated EMF are small and very difficult to relate to potential health effects. There is no convincing evidence of frequency and power density windows of response to these fields.

Shocks and burns can be the adverse indirect effects of high-frequency EMF involving human contact with metallic objects in the field. At frequencies of 100 kHz–110 MHz (the upper limit of the FM broadcast band), the threshold levels of contact current that produce effects ranging from perception to severe pain do not vary significantly as a function of the field frequency. The threshold for perception ranges from 25 to 40 mA in individuals of different sizes, and that for pain from approximately 30 to 55 mA; above 50 mA there may be severe burns at the site of tissue contact with a metallic conductor in the field.

GUIDELINES FOR LIMITING EMF EXPOSURE

Occupational and general public exposure limitations

The occupationally exposed population consists of adults who are generally exposed under known conditions and are trained to be aware of potential risk and to take appropriate precautions. By contrast, the general public comprises individuals of all ages and of varying health status, and may include particularly susceptible groups or individuals. In many cases, members of the public are unaware of their exposure to EMF. Moreover, individual members of the public cannot reasonably be expected to take precautions to minimize or avoid exposure. It is these considerations that underlie the adoption of more stringent exposure restrictions for the public than for the occupationally exposed population.

Basic restrictions and reference levels

Restrictions on the effects of exposure are based on established health effects and are termed basic restrictions. Depending on frequency, the physical quantities used to specify the basic restrictions on exposure to EMF are current density, SAR, and power density. Protection against adverse health effects requires that these basic restrictions are not exceeded.

Reference levels of exposure are provided for comparison with measured values of physical quantities; compliance with all reference levels given in these guidelines will ensure compliance with basic restrictions. If measured values are higher than reference levels, it does not necessarily follow that the basic restrictions have been exceeded, but a more detailed analysis is necessary to assess compliance with the basic restrictions.

General statement on safety factors

There is insufficient information on the biological and health effects of EMF exposure of human populations and experimental animals to provide a rigorous basis for establishing safety factors over the whole frequency range and for all frequency modulations. In addition, some of the uncertainty regarding the appropriate safety factor derives from a lack of knowledge regarding the appropriate dosimetry (Repacholi 1998). The following general variables were considered in the development of safety factors for high-frequency fields:

- effects of EMF exposure under severe environmental conditions (high temperature, etc.) and/or high activity levels; and
- the potentially higher thermal sensitivity in certain population groups, such as the frail and/or elderly, infants and young children, and people with diseases or taking medications that compromise thermal tolerance.

The following additional factors were taken into account in deriving reference levels for high-frequency fields:

- differences in absorption of electromagnetic energy by individuals of different sizes and different orientations relative to the field; and
- reflection, focusing, and scattering of the incident field, which can result in enhanced localized absorption of high-frequency energy.

Basic restrictions

Different scientific bases were used in the development of basic exposure restrictions for various frequency ranges:

- Between 1 Hz and 10 MHz, basic restrictions are provided on current density to prevent effects on nervous system functions;
- Between 100 kHz and 10 GHz, basic restrictions on SAR are provided to prevent whole-body heat stress and excessive localized tissue heating; in the 100 kHz–10 MHz range, restrictions are provided on both current density and SAR; and
- Between 10 and 300 GHz, basic restrictions are provided on power density to prevent excessive heating in tissue at or near the body surface.

In the frequency range from a few Hz to 1 kHz, for levels of induced current density above 100 mA m^{-2}, the thresholds for acute changes in central nervous system excitability and other acute effects such as reversal of the visually evoked potential are exceeded. In view of the safety considerations above, it was decided that, for frequencies in the range 4 Hz to 1 kHz, occupational exposure should be limited to fields that induce current densities less than 10 mA m^{-2}, i.e., to use a safety factor of 10. For the general public an additional factor of 5 is applied, giving a basic exposure restriction of 2 mA m^{-2}. Below 4 Hz and above 1 kHz, the basic restriction on induced current density increases progressively, corresponding to the increase in the threshold for nerve stimulation for these frequency ranges.

Established biological and health effects in the frequency range from 10 MHz to a few GHz are consistent with responses to a body temperature rise of more than 1°C. This level of temperature increase results from exposure of individuals under moderate environmental conditions to a whole-body SAR of approximately 4 W kg^{-1} for about 30 min. A whole-body average SAR of 0.4 W kg^{-1} has therefore been chosen as the restriction that provides adequate protection for occupational exposure. An additional safety factor of 5 is introduced for exposure of the public, giving an average whole-body SAR limit of 0.08 W kg^{-1}.

The lower basic restrictions for exposure of the general public take into account the fact that their age and health status may differ from those of workers.

In the low-frequency range, there are currently few data relating transient currents to health effects. The ICNIRP therefore recommends that the restrictions on current densities induced by transient or very short-term peak fields be regarded as instantaneous values which should not be time-averaged.

The basic restrictions for current densities, whole-body average SAR, and localized SAR for frequencies between 1 Hz and 10 GHz are presented in Table 4, and those for power densities for frequencies of 10–300 GHz are presented in Table 5.

REFERENCE LEVELS

Where appropriate, the reference levels are obtained from the basic restrictions by mathematical modeling and by extrapolation from the results of laboratory investigations at specific frequencies. They are given for the condition of maximum coupling of the field to the exposed individual, thereby providing maximum protection. Tables 6 and 7 summarize the reference levels for occupational exposure and exposure of the general public, respectively, and the reference levels are illustrated in Figs. 1 and 2. The reference levels are intended to be spatially averaged values over the entire body of the exposed individual, but with the important proviso that the basic restrictions on localized exposure are not exceeded.

For low-frequency fields, several computational and measurement methods have been developed for deriving field-strength reference levels from the basic restrictions.

Table 4. Basic restrictions for time varying electric and magnetic fields for frequencies up to 10 GHz.[a]

Exposure characteristics	Frequency range	Current density for head and trunk (mA m^{-2}) (rms)	Whole-body average SAR (W kg^{-1})	Localized SAR (head and trunk) (W kg^{-1})	Localized SAR (limbs) (W kg^{-1})
Occupational exposure	up to 1 Hz	40	—	—	—
	1–4 Hz	$40/f$	—	—	—
	4 Hz–1 kHz	10	—	—	—
	1–100 kHz	$f/100$	—	—	—
	100 kHz–10 MHz	$f/100$	0.4	10	20
	10 MHz–10 GHz	—	0.4	10	20
General public exposure	up to 1 Hz	8	—	—	—
	1–4 Hz	$8/f$	—	—	—
	4 Hz–1 kHz	2	—	—	—
	1–100 kHz	$f/500$	—	—	—
	100 kHz–10 MHz	$f/500$	0.08	2	4
	10 MHz–10 GHz	—	0.08	2	4

[a] Note:
1. f is the frequency in hertz.
2. Because of electrical inhomogeneity of the body, current densities should be averaged over a cross-section of 1 cm^2 perpendicular to the current direction.
3. For frequencies up to 100 kHz, peak current density values can be obtained by multiplying the rms value by $\sqrt{2}$ ($\sim$1.414). For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$.
4. For frequencies up to 100 kHz and for pulsed magnetic fields, the maximum current density associated with the pulses can be calculated from the rise/fall times and the maximum rate of change of magnetic flux density. The induced current density can then be compared with the appropriate basic restriction.
5. All SAR values are to be averaged over any 6-min period.
6. Localized SAR averaging mass is any 10 g of contiguous tissue; the maximum SAR so obtained should be the value used for the estimation of exposure.
7. For pulses of duration t_p the equivalent frequency to apply in the basic restrictions should be calculated as $f = 1/(2t_p)$. Additionally, for pulsed exposures in the frequency range 0.3 to 10 GHz and for localized exposure of the head, in order to limit or avoid auditory effects caused by thermoelastic expansion, an additional basic restriction is recommended. This is that the SA should not exceed 10 mJ kg^{-1} for workers and 2mJ kg^{-1} for the general public, averaged over 10 g tissue.

Table 5. Basic restrictions for power density for frequencies between 10 and 300 GHz.[a]

Exposure characteristics	Power density (W m^{-2})
Occupational exposure	50
General public	10

[a] Note:
1. Power densities are to be averaged over any 20 cm^2 of exposed area and any $68/f^{1.05}$-min period (where f is in GHz) to compensate for progressively shorter penetration depth as the frequency increases.
2. Spatial maximum power densities, averaged over 1 cm^2, should not exceed 20 times the values above.

The simplifications that have been used to date did not account for phenomena such as the inhomogeneous distribution and anisotropy of the electrical conductivity and other tissue factors of importance for these calculations.

The frequency dependence of the reference field levels is consistent with data on both biological effects and coupling of the field.

Magnetic field models assume that the body has a homogeneous and isotropic conductivity and apply simple circular conductive loop models to estimate induced currents in different organs and body regions, e.g., the head, by using the following equation for a pure sinusoidal field at frequency f derived from Faraday's law of induction:

$$J = \pi R f \sigma \mathrm{B}, \quad (4)$$

where B is the magnetic flux density and R is the radius of the loop for induction of the current. More complex models use an ellipsoidal model to represent the trunk or the whole body for estimating induced current densities at the surface of the body (Reilly 1989, 1992).

If, for simplicity, a homogeneous conductivity of 0.2 S m^{-1} is assumed, a 50-Hz magnetic flux density of 100 μT generates current densities between 0.2 and 2 mA m^{-2} in the peripheral area of the body (CRP 1997). According to another analysis (NAS 1996), 60-Hz exposure levels of 100 μT correspond to average current densities of 0.28 mA m^{-2} and to maximum current densities of approximately 2 mA m^{-2}. More realistic calculations based on anatomically and electrically refined models (Xi and Stuchly 1994) resulted in maximum current densities exceeding 2 mA m^{-2} for a 100-μT field at 60 Hz. However, the presence of biological cells affects the spatial pattern of induced currents and fields, resulting in significant differences in both magnitude (a factor of 2 greater) and patterns of flow of the induced current compared with those predicted by simplified analyses (Stuchly and Xi 1994).

Electric field models must take into account the fact that, depending on the exposure conditions and the size, shape, and position of the exposed body in the field, the surface charge density can vary greatly, resulting in a variable and non-uniform distribution of currents inside the body. For sinusoidal electric fields at frequencies below about 10 MHz, the magnitude of the induced current density inside the body increases with frequency. The induced current density distribution varies inversely with the body cross-section and may be relatively high in the neck and ankles. The exposure level of 5 kV m^{-1} for exposure of the general public corresponds, under worst-case conditions, to an induced current density of about 2 mA m^{-2} in the neck and trunk of the body if the E-field vector is parallel to the body axis (ILO 1994; CRP 1997). However, the current density induced by 5 kV m^{-1} will comply with the basic restrictions under realistic worst-case exposure conditions.

For purposes of demonstrating compliance with the basic restrictions, the reference levels for the electric and magnetic fields should be considered separately and not additively. This is because, for protection purposes, the currents induced by electric and magnetic fields are not additive.

For the specific case of occupational exposures at frequencies up to 100 kHz, the derived electric fields can be increased by a factor of 2 under conditions in which adverse indirect effects from contact with electrically charged conductors can be excluded.

At frequencies above 10 MHz, the derived electric and magnetic field strengths were obtained from the whole-body SAR basic restriction using computational and experimental data. In the worst case, the energy coupling reaches a maximum between 20 MHz and several hundred MHz. In this frequency range, the derived reference levels have minimum values. The derived magnetic field strengths were calculated from the electric field strengths by using the far-field relationship between E and H (E/H = 377 ohms). In the near-field, the SAR frequency dependence curves are no longer valid; moreover, the contributions of the electric and magnetic field components have to be considered separately. For a conservative approximation, field exposure levels can be used for near-field assessment since the coupling of energy from the electric or magnetic field contribution cannot exceed the SAR restrictions. For a less conservative assessment, basic restrictions on the whole-body average and local SAR should be used.

Reference levels for exposure of the general public have been obtained from those for occupational exposure by using various factors over the entire frequency range. These factors have been chosen on the basis of effects that are recognized as specific and relevant for the various frequency ranges. Generally speaking, the factors follow the basic restrictions over the entire frequency range, and their values correspond to the mathematical relation between the quantities of the basic restrictions and the derived levels as described below:

- In the frequency range up to 1 kHz, the general public reference levels for electric fields are one-half of the values set for occupational exposure. The value of 10 kV m^{-1} for a 50-Hz or 8.3 kV m^{-1} for a 60-Hz occupational exposure includes a sufficient safety margin to prevent stimulation effects from contact currents under all possible conditions. Half of this value was chosen for the general public reference levels, i.e.,

Table 6. Reference levels for occupational exposure to time-varying electric and magnetic fields (unperturbed rms values).[a]

Frequency range	E-field strength ($V\ m^{-1}$)	H-field strength ($A\ m^{-1}$)	B-field (μT)	Equivalent plane wave power density S_{eq} ($W\ m^{-2}$)
up to 1 Hz	—	1.63×10^5	2×10^5	—
1–8 Hz	20,000	$1.63 \times 10^5/f^2$	$2 \times 10^5/f^2$	—
8–25 Hz	20,000	$2 \times 10^4/f$	$2.5 \times 10^4/f$	—
0.025–0.82 kHz	$500/f$	$20/f$	$25/f$	—
0.82–65 kHz	610	24.4	30.7	—
0.065–1 MHz	610	$1.6/f$	$2.0/f$	—
1–10 MHz	$610/f$	$1.6/f$	$2.0/f$	—
10–400 MHz	61	0.16	0.2	10
400–2,000 MHz	$3f^{1/2}$	$0.008f^{1/2}$	$0.01f^{1/2}$	$f/40$
2–300 GHz	137	0.36	0.45	50

[a] Note:
1. f as indicated in the frequency range column.
2. Provided that basic restrictions are met and adverse indirect effects can be excluded, field strength values can be exceeded.
3. For frequencies between 100 kHz and 10 GHz, S_{eq}, E^2, H^2, and B^2 are to be averaged over any 6-min period.
4. For peak values at frequencies up to 100 kHz see Table 4, note 3.
5. For peak values at frequencies exceeding 100 kHz see Figs. 1 and 2. Between 100 kHz and 10 MHz, peak values for the field strengths are obtained by interpolation from the 1.5-fold peak at 100 kHz to the 32-fold peak at 10 MHz. For frequencies exceeding 10 MHz it is suggested that the peak equivalent plane wave power density, as averaged over the pulse width, does not exceed 1,000 times the S_{eq} restrictions, or that the field strength does not exceed 32 times the field strength exposure levels given in the table.
6. For frequencies exceeding 10 GHz, S_{eq}, E^2, H^2, and B^2 are to be averaged over any $68/f^{1.05}$-min period (f in GHz).
7. No E-field value is provided for frequencies <1 Hz, which are effectively static electric fields. Electric shock from low impedance sources is prevented by established electrical safety procedures for such equipment.

Table 7. Reference levels for general public exposure to time-varying electric and magnetic fields (unperturbed rms values).[a]

Frequency range	E-field strength ($V\ m^{-1}$)	H-field strength ($A\ m^{-1}$)	B-field (μT)	Equivalent plane wave power density S_{eq} ($W\ m^{-2}$)
up to 1 Hz	—	3.2×10^4	4×10^4	—
1–8 Hz	10,000	$3.2 \times 10^4/f^2$	$4 \times 10^4/f^2$	—
8–25 Hz	10,000	$4,000/f$	$5,000/f$	—
0.025–0.8 kHz	$250/f$	$4/f$	$5/f$	—
0.8–3 kHz	$250/f$	5	6.25	—
3–150 kHz	87	5	6.25	—
0.15–1 MHz	87	$0.73/f$	$0.92/f$	—
1–10 MHz	$87/f^{1/2}$	$0.73/f$	$0.92/f$	—
10–400 MHz	28	0.073	0.092	2
400–2,000 MHz	$1.375f^{1/2}$	$0.0037f^{1/2}$	$0.0046f^{1/2}$	$f/200$
2–300 GHz	61	0.16	0.20	10

[a] Note:
1. f as indicated in the frequency range column.
2. Provided that basic restrictions are met and adverse indirect effects can be excluded, field strength values can be exceeded.
3. For frequencies between 100 kHz and 10 GHz, S_{eq}, E^2, H^2, and B^2 are to averaged over any 6-min period.
4. For peak values at frequencies up to 100 kHz see Table 4, note 3.
5. For peak values at frequencies exceeding 100 kHz see Figs. 1 and 2. Between 100 kHz and 10 MHz, peak values for the field strengths are obtained by interpolation from the 1.5-fold peak at 100 kHz to the 32-fold peak at 10 MHz. For frequencies exceeding 10 MHz it is suggested that the peak equivalent plane wave power density, as averaged over the pulse width does not exceed 1,000 times the S_{eq} restrictions, or that the field strength does not exceed 32 times the field strength exposure levels given in the table.
6. For frequencies exceeding 10 GHz, S_{eq}, E^2, H^2, and B^2 are to be averaged over any $68/f^{1.05}$-min period (f in GHz).
7. No E-field value is provided for frequencies <1 Hz, which are effectively static electric fields. perception of surface electric charges will not occur at field strengths less than 25 kVm^{-1}. Spark discharges causing stress or annoyance should be avoided.

5 $kV\ m^{-1}$ for 50 Hz or 4.2 $kV\ m^{-1}$ for 60 Hz, to prevent adverse indirect effects for more than 90% of exposed individuals;

- In the low-frequency range up to 100 kHz, the general public reference levels for magnetic fields are set at a factor of 5 below the values set for occupational exposure;
- In the frequency range 100 kHz–10 MHz, the general public reference levels for magnetic fields have been increased compared with the limits given in the 1988 IRPA guideline. In that guideline, the magnetic field strength reference levels were calculated from the electric field strength reference levels by using the far-field

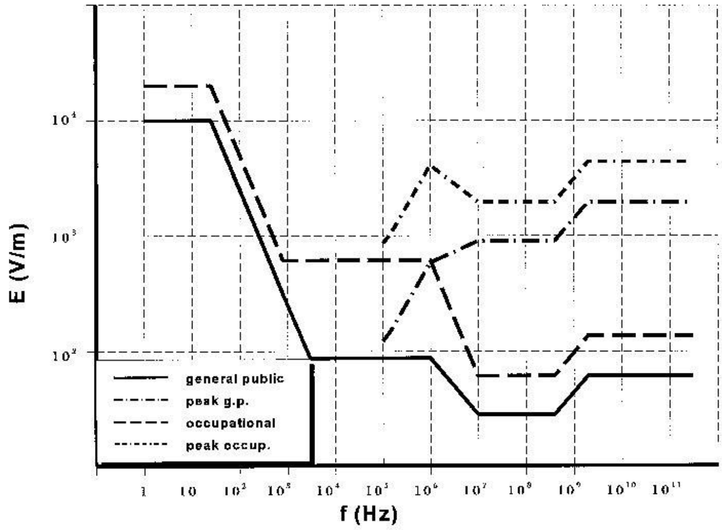

Fig. 1. Reference levels for exposure to time varying electric fields (compare Tables 6 and 7).

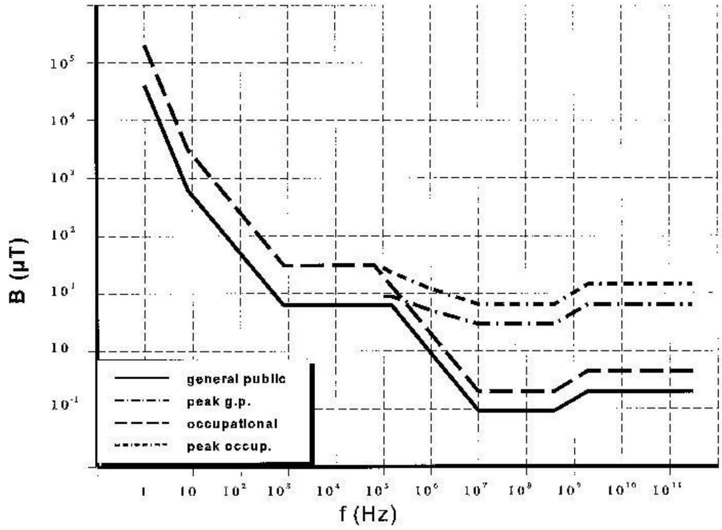

Fig. 2. Reference levels for exposure to time varying magnetic fields (compare Tables 6 and 7).

formula relating E and H. These reference levels are too conservative, since the magnetic field at frequencies below 10 MHz does not contribute significantly to the risk of shocks, burns, or surface charge effects that form a major basis for limiting occupational exposure to electric fields in that frequency range;

- In the high-frequency range 10 MHz–10 GHz, the general public reference levels for electric and magnetic fields are lower by a factor of 2.2 than those set for occupational exposure. The factor of 2.2 corresponds to the square root of 5, which is the safety factor between the basic restrictions for occupational exposure and those for general public exposure. The square root is used to relate the quantities "field strength" and "power density;"

- In the high-frequency range 10–300 GHz, the general public reference levels are defined by the power density, as in the basic restrictions, and are lower by a factor of 5 than the occupational exposure restrictions;
- Although little information is available on the relation between biological effects and peak values of pulsed fields, it is suggested that, for frequencies exceeding 10 MHz, S_{eq} as averaged over the pulse width should not exceed 1,000 times the reference levels or that field strengths should not exceed 32 times the field strength reference levels given in Tables 6 and 7 or shown in Figs. 1 and 2. For frequencies between about 0.3 GHz and several GHz, and for localized exposure of the head, in order to limit or avoid auditory effects caused by thermoelastic expansion the specific absorption from pulses must limited. In this frequency range, the threshold SA of 4–16 mJ kg^{-1} for producing this effect corresponds, for 30-μs pulses, to peak SAR values of 130–520 W kg^{-1} in the brain. Between 100 kHz and 10 MHz, peak values for the field strengths in Figs. 1 and 2 are obtained by interpolation from the 1.5-fold peak at 100 kHz to the 32-fold peak at 10 MHz.
- In Tables 6 and 7, as well as in Figs. 1 and 2, different frequency break-points occur for occupational and general public derived reference levels. This is a consequence of the varying factors used to derive the general public reference levels, while generally keeping the frequency dependence the same for both occupational and general public levels.

REFERENCE LEVELS FOR CONTACT AND INDUCED CURRENTS

Up to 110 MHz, which includes the FM radio transmission frequency band, reference levels for contact current are given above which caution must be exercised to avoid shock and burn hazards. The point contact reference levels are presented in Table 8. Since the threshold contact currents that elicit biological responses in children and adult women are approximately one-half and two-thirds, respectively, of those for adult men, the reference levels for contact current for the general public are set lower by a factor of 2 than the values for occupational exposure.

For the frequency range 10–110 MHz, reference levels are provided for limb currents that are below the basic restrictions on localized SAR (see Table 9).

SIMULTANEOUS EXPOSURE TO MULTIPLE FREQUENCY FIELDS

It is important to determine whether, in situations of simultaneous exposure to fields of different frequencies, these exposures are additive in their effects. Additivity should be examined separately for the effects of thermal and electrical stimulation, and the basic restrictions below should be met. The formulae below apply to relevant frequencies under practical exposure situations.

For electrical stimulation, relevant for frequencies up to 10 MHz, induced current densities should be added according to

$$\sum_{i=1\ \mathrm{Hz}}^{10\ \mathrm{MHz}} \frac{J_i}{J_{L,i}} \leq 1. \qquad (5)$$

For thermal effects, relevant above 100 kHz, SAR and power density values should be added according to:

$$\sum_{i=100\ \mathrm{kHz}}^{10\ \mathrm{GHz}} \frac{SAR_i}{SAR_L} + \sum_{i>10\ \mathrm{GHz}}^{300\ \mathrm{GHz}} \frac{S_i}{S_L} \leq 1, \qquad (6)$$

where

J_i = the current density induced at frequency i;
$J_{L,i}$ = the induced current density restriction at frequency i as given in Table 4;
SAR_i = the SAR caused by exposure at frequency i;
SAR_L = the SAR limit given in Table 4;
S_L = the power density limit given in Table 5; and
S_i = the power density at frequency i.

For practical application of the basic restrictions, the following criteria regarding reference levels of field strengths should be applied.

Table 8. Reference levels for time varying contact currents from conductive objects.[a]

Exposure characteristics	Frequency range	Maximum contact current (mA)
Occupational exposure	up to 2.5 kHz	1.0
	2.5–100 kHz	0.4*f*
	100 kHz–110 MHz	40
General public exposure	up to 2.5 kHz	0.5
	2.5–100 kHz	0.2*f*
	100 kHz–110 MHz	20

[a] *f* is the frequency in kHz.

Table 9. Reference levels for current induced in any limb at frequencies between 10 and 110 MHz.[a]

Exposure characteristics	Current (mA)
Occupational exposure	100
General public	45

[a] Note:
1. The public reference level is equal to the occupational reference level divided by $\sqrt{5}$.
2. For compliance with the basic restriction on localized SAR, the square root of the time-averaged value of the square of the induced current over any 6-min period forms the basis of the reference levels.

For induced current density and electrical stimulation effects, relevant up to 10 MHz, the following two requirements should be applied to the field levels:

$$\sum_{i=1\,\mathrm{Hz}}^{1\,\mathrm{MHz}} \frac{E_i}{E_{L,i}} + \sum_{i>1\,\mathrm{MHz}}^{10\,\mathrm{MHz}} \frac{E_i}{a} \leq 1, \tag{7}$$

and

$$\sum_{j=1\,\mathrm{Hz}}^{65\,\mathrm{kHz}} \frac{H_j}{H_{L,j}} + \sum_{j>65\,\mathrm{kHz}}^{10\,\mathrm{MHz}} \frac{H_j}{b} \leq 1, \tag{8}$$

where

E_i = the electric field strength at frequency i;
$E_{L,\,i}$ = the electric field reference level from Tables 6 and 7;
H_j = the magnetic field strength at frequency j;
$H_{L,\,j}$ = the magnetic field reference level from Tables 6 and 7;
a = 610 V m^{-1} for occupational exposure and 87 V m^{-1} for general public exposure; and
b = 24.4 A m^{-1} (30.7 μT) for occupational exposure and 5 A m^{-1} (6.25 μT) for general public exposure.

The constant values a and b are used above 1 MHz for the electric field and above 65 kHz for the magnetic field because the summation is based on induced current densities and should not be mixed with thermal considerations. The latter forms the basis for $E_{L,i}$ and $H_{L,j}$ above 1 MHz and 65 kHz, respectively, found in Tables 6 and 7.

For thermal considerations, relevant above 100 kHz, the following two requirements should be applied to the field levels:

$$\sum_{i=100\,\mathrm{kHz}}^{1\,\mathrm{MHz}} \left(\frac{E_i}{c}\right)^2 + \sum_{i>1\,\mathrm{MHz}}^{300\,\mathrm{GHz}} \left(\frac{E_i}{E_{L,i}}\right)^2 \leq 1, \tag{9}$$

and

$$\sum_{j=100\,\mathrm{kHz}}^{1\,\mathrm{MHz}} \left(\frac{H_j}{d}\right)^2 + \sum_{j>1\,\mathrm{MHz}}^{300\,\mathrm{GHz}} \left(\frac{H_j}{H_{L,j}}\right)^2 \leq 1, \tag{10}$$

where

E_i = the electric field strength at frequency i;
$E_{L,\,i}$ = the electric field reference level from Tables 6 and 7;
H_j = the magnetic field strength at frequency j;
$H_{L,\,i}$ = the magnetic field reference level from Tables 6 and 7;
c = $610/f$ V m^{-1} (f in MHz) for occupational exposure and $87/f^{1/2}$ V m^{-1} for general public exposure; and
d = $1.6/f$ A m^{-1} (f in MHz) for occupational exposure and $0.73/f$ for general public exposure.

For limb current and contact current, respectively, the following requirements should be applied:

$$\sum_{k=10\,\mathrm{MHz}}^{110\,\mathrm{MHz}} \left(\frac{I_k}{I_{L,k}}\right)^2 \leq 1 \qquad \sum_{n=1\,\mathrm{Hz}}^{110\,\mathrm{MHz}} \frac{I_n}{I_{C,n}} \leq 1, \tag{11}$$

where

I_k = the limb current component at frequency k;
$I_{L,\,k}$ = the reference level of limb current (see Table 9);
I_n = the contact current component at frequency n; and
$I_{C,\,n}$ = the reference level of contact current at frequency n (see Table 8).

The above summation formulae assume worst-case conditions among the fields from the multiple sources. As a result, typical exposure situations may in practice require less restrictive exposure levels than indicated by the above formulae for the reference levels.

PROTECTIVE MEASURES

ICNIRP notes that the industries causing exposure to electric and magnetic fields are responsible for ensuring compliance with all aspects of the guidelines.

Measures for the protection of workers include engineering and administrative controls, personal protection programs, and medical surveillance (ILO 1994). Appropriate protective measures must be implemented when exposure in the workplace results in the basic restrictions being exceeded. As a first step, engineering controls should be undertaken wherever possible to reduce device emissions of fields to acceptable levels. Such controls include good safety design and, where necessary, the use of interlocks or similar health protection mechanisms.

Administrative controls, such as limitations on access and the use of audible and visible warnings, should be used in conjunction with engineering controls. Personal protection measures, such as protective clothing, though useful in certain circumstances, should be regarded as a last resort to ensure the safety of the worker; priority should be given to engineering and administrative controls wherever possible. Furthermore, when such items as insulated gloves are used to protect individuals from high-frequency shock and burns, the basic restrictions must not be exceeded, since the insulation protects only against indirect effects of the fields.

With the exception of protective clothing and other personal protection, the same measures can be applied to the general public whenever there is a possibility that the general public reference levels might be exceeded. It is also essential to establish and implement rules that will prevent:

- interference with medical electronic equipment and devices (including cardiac pacemakers);

- detonation of electro-explosive devices (detonators); and
- fires and explosions resulting from ignition of flammable materials by sparks caused by induced fields, contact currents, or spark discharges.

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APPENDIX

Glossary

Absorption. In radio wave propagation, attenuation of a radio wave due to dissipation of its energy, i.e., conversion of its energy into another form, such as heat.

Athermal effect. Any effect of electromagnetic energy on a body that is not a heat-related effect.

Blood-brain barrier. A functional concept developed to explain why many substances that are transported by blood readily enter other tissues but do not enter the brain; the "barrier" functions as if it were a continuous membrane lining the vasculature of the brain. These brain capillary endothelial cells form a nearly continuous barrier to entry of substances into the brain from the vasculature.

Conductance. The reciprocal of resistance. Expressed in siemens (S).

Conductivity, electrical. The scalar or vector quantity which, when multiplied by the electric field strength, yields the conduction current density; it is the reciprocal of resistivity. Expressed in siemens per meter (S m^{-1}).

Continuous wave. A wave whose successive oscillations are identical under steady-state conditions.

Current density. A vector of which the integral over a given surface is equal to the current flowing through the surface; the mean density in a linear conductor is equal to the current divided by the cross-sectional area of the conductor. Expressed in ampere per square meter (A m^{-2}).

Depth of penetration. For a plane wave electromagnetic field (EMF), incident on the boundary of a good conductor, depth of penetration of the wave is the depth at which the field strength of the wave has been reduced to 1/e, or to approximately 37% of its original value.

Dielectric constant. See permittivity.

Dosimetry. Measurement, or determination by calculation, of internal electric field strength or induced current density, of the specific energy absorption, or specific energy absorption rate distribution, in humans or animals exposed to electromagnetic fields.

Electric field strength. The force (E) on a stationary unit positive charge at a point in an electric field; measured in volt per meter (V m^{-1}).

Electromagnetic energy. The energy stored in an electromagnetic field. Expressed in joule (J).

ELF. Extremely low frequency; frequency below 300 Hz.

EMF. Electric, magnetic, and electromagnetic fields.

Far field. The region where the distance from a radiating antenna exceeds the wavelength of the radiated EMF; in the far-field, field components (E and H) and the direction of propagation are mutually perpendicular, and the shape of the field pattern is independent of the distance from the source at which it is taken.

Frequency. The number of sinusoidal cycles completed by electromagnetic waves in 1 s; usually expressed in hertz (Hz).

Impedance, wave. The ratio of the complex number (vector) representing the transverse electric field at a point to that representing the transverse magnetic field at that point. Expressed in ohm (Ω).

Magnetic field strength. An axial vector quantity, H, which, together with magnetic flux density, specifies a magnetic field at any point in space, and is expressed in ampere per meter (A m^{-1}).

Magnetic flux density. A vector field quantity, B, that results in a force that acts on a moving charge or charges, and is expressed in tesla (T).

Magnetic permeability. The scalar or vector quantity which, when multiplied by the magnetic field strength, yields magnetic flux density; expressed in henry per meter ($H\ m^{-1}$). *Note:* For isotropic media, magnetic permeability is a scalar; for anisotropic media, it is a tensor quantity.

Microwaves. Electromagnetic radiation of sufficiently short wavelength for which practical use can be made of waveguide and associated cavity techniques in its transmission and reception. *Note:* The term is taken to signify radiations or fields having a frequency range of 300 MHz–300 GHz.

Near field. The region where the distance from a radiating antenna is less than the wavelength of the radiated EMF. *Note:* The magnetic field strength (multiplied by the impedance of space) and the electric field strength are unequal and, at distances less than one-tenth of a wavelength from an antenna, vary inversely as the square or cube of the distance if the antenna is small compared with this distance.

Non-ionizing radiation (NIR). Includes all radiations and fields of the electromagnetic spectrum that do not normally have sufficient energy to produce ionization in matter; characterized by energy per photon less than about 12 eV, wavelengths greater than 100 nm, and frequencies lower than 3×10^{15} Hz.

Occupational exposure. All exposure to EMF experienced by individuals in the course of performing their work.

Permittivity. A constant defining the influence of an isotropic medium on the forces of attraction or repulsion between electrified bodies, and expressed in farad per metre ($F\ m^{-1}$); *relative permittivity* is the permittivity of a material or medium divided by the permittivity of vacuum.

Plane wave. An electromagnetic wave in which the electric and magnetic field vectors lie in a plane perpendicular to the direction of wave propagation, and the magnetic field strength (multiplied by the impedance of space) and the electric field strength are equal.

Power density. In radio wave propagation, the power crossing a unit area normal to the direction of wave propagation; expressed in watt per square meter ($W\ m^{-2}$).

Public exposure. All exposure to EMF experienced by members of the general public, excluding occupational exposure and exposure during medical procedures.

Radiofrequency (RF). Any frequency at which electromagnetic radiation is useful for telecommunication. *Note:* In this publication, radiofrequency refers to the frequency range 300 Hz –300 GHz.

Resonance. The change in amplitude occurring as the frequency of the wave approaches or coincides with a natural frequency of the medium; whole-body absorption of electromagnetic waves presents its highest value, i.e., the resonance, for frequencies (in MHz) corresponding approximately to $114/L$, where L is the height of the individual in meters.

Root mean square (rms). Certain electrical effects are proportional to the square root of the mean of the square of a periodic function (over one period). This value is known as the effective, or root-mean-square (rms) value, since it is derived by first squaring the function, determining the mean value of the squares obtained, and taking the square root of that mean value.

Specific energy absorption. The energy absorbed per unit mass of biological tissue, (SA) expressed in joule per kilogram ($J\ kg^{-1}$); specific energy absorption is the time integral of specific energy absorption rate.

Specific energy absorption rate (SAR). The rate at which energy is absorbed in body tissues, in watt per kilogram ($W\ kg^{-1}$); SAR is the dosimetric measure that has been widely adopted at frequencies above about 100 kHz.

Wavelength. The distance between two successive points of a periodic wave in the direction of propagation, at which the oscillation has the same phase.

■ ■

Note

Equation 11 in this publication (Health Physics, 1998) was subsequently amended by the ICNIRP Commission in the 1999 reference book "Guidelines on Limiting Exposure to Non-Ionizing Radiation", a reference book based on guidelines on limiting exposure to non-ionizing radiation and statements on special applications. R. Matthes, J.H. Bernhardt, A.F. McKinlay (eds.) International Commission on Non-Ionizing Radiation Protection 1999, ISBN 3-9804789-6-3. The amended version is available below.

"For limb current and contact current, respectively, the following requirements should be applied:

$$\sum_{k=10MHz}^{110MHz}\left(\frac{I_k}{I_{L,k}}\right)^2 \le 1 \qquad \sum_{n=1Hz}^{10MHz}\frac{I_n}{I_{C,n}} \le 1 \qquad \sum_{n=100kHz}^{110MHz}\left(\frac{I_n}{I_{C,n}}\right)^2 \le 1 \qquad (11)$$

where
I_k is the limb current component at frequency k
$I_{L,k}$ is the reference level of limb current (see Table 9)
I_n is the contact current component at frequency n
$I_{C,n}$ is the reference level of contact current at frequency n (see Table 8).

The above summation formulae assume worst-case conditions among the fields from the multiple sources. As a result, typical exposure situations may in practice require less restrictive exposure levels than indicated by the above formulae for the reference levels."

Ref: Excerpt from "Guidelines on Limiting Exposure to Non-Ionizing Radiation", a reference book based on guidelines on limiting exposure to non-ionizing radiation and statements on special applications. R. Matthes, J.H. Bernhardt, A.F. McKinlay (eds.) International Commission on Non-Ionizing Radiation Protection 1999, ISBN 3-9804789-6-3.

RESPONSE TO QUESTIONS AND COMMENTS ON THE GUIDELINES FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC, MAGNETIC, AND ELECTROMAGNETIC FIELDS (up to 300 GHz)*

1) *Question:* What dosimetric models were used by ICNIRP to derive the reference levels from the basic restrictions?

Answer: To a limited extent, the ICNIRP guidelines provide a description of the dosimetric models that were used, and give references to the primary literature describing these models in detail. However, for purposes of brevity, ICNIRP decided not to include a detailed discussion of these dosimetric models in its published guidelines.

2) *Question:* On which specific data are the guidelines for magnetic fields at frequencies less than 4 Hz based?

Answer: The guidelines for magnetic fields below 4 Hz are ramped in a manner that joins the ELF reference levels with the values previously recommended by ICNIRP for static fields, i.e., at 0 Hz (ICNIRP. Guidelines on limits of exposure to static magnetic fields. Health Physics 66:100-106; 1994), and they are not based on specific biological studies.

3) *Question:* Why was 10 g chosen as the averaging mass without defining a regular tissue geometry?

Answer: The 10 g of tissue is intended to be a mass of contiguous tissue with nearly homogeneous electrical properties. In specifying a contiguous mass of tissue, ICNIRP recognizes that this concept can be used in computational dosimetry, but may present difficulties for direct physical measurements. A simple geometry such as a cubic tissue mass can be used provided that the calculated dosimetric quantities have conservative values relative to the exposure guidelines.

4) *Question:* Is the 10 g averaging mass appropriate for the limbs of the body?

Answer: ICNIRP recognizes that, under certain exposure conditions, the localized SAR basic restrictions for occupational and general public exposures may be exceeded in the wrist by a small amount. However, this condition is not considered to present any significant health risk.

* This response was published in Health Physics 75 (4), 438-439; 1998

5) *Question:* Would exposure to RF fields at the reference levels recommended for workers or members of the general public lead to an increase in body temperature?

Answer: Adherence to the ICNIRP guidelines under either occupational or public exposure conditions would prevent an increase in temperature to levels that lie outside of the normal range of variation associated with body functions.

6) *Question:* Under certain circumstances, the fields emanating from appliances and machine tools can exceed the ICNIRP reference levels. Is there a problem with adhering to the ICNIRP guidelines under these circumstances?

Answer: ICNIRP recognizes that a number of common devices emit localized fields in excess of the reference levels. However, this generally occurs under conditions of exposure where the basic restrictions are not exceeded because of weak coupling between the field and the body.

7) *Question:* What is the rationale for recommending a public exposure guideline of 5 kV m^{-1} at 50 Hz and 4.17 at 60 Hz?

Answer: The reference levels for electric fields at power frequencies were set to limit indirect effects of contact with electrical conductors in the field. Provided that adverse health impacts of indirect effects of exposure (such as microshocks) can be avoided, ICNIRP recognizes that the general public reference levels at power frequencies can be exceeded provided that the basic restriction of 2 mA m^{-2} is not surpassed. In many practical exposure situations external power frequency electric fields at the reference levels will induce current densities in central nervous tissues that are well below the basic restrictions. Recent dosimetry calculations indicate that the reference levels for power-frequency magnetic fields are conservative guidelines relative to meeting the basic restrictions on current density for both public and occupational exposures (Dimbylow, P.J. Induced current densities from low-frequency magnetic fields in a 2 mm resolution, anatomically realistic model of the body. Phys. Med. Biol. 43:221-230; 1998).

8) *Question:* Why did ICNIRP not recommend guidelines for pulsed and/or transient fields at low frequencies?

Answer: ICNIRP has provided frequency-dependent basic restrictions and reference levels from which a hazard assessment and exposure guidelines on

pulsed and/or transient sources can be derived. A conservative approach involves representing a pulsed or transient EMF signal as a Fourier spectrum of its components in each frequency range, which can then be compared with the ICNIRP reference levels for those frequencies. The summation formulae for simultaneous exposure to multiple frequency fields given in the ICNIRP guidelines can also be applied for purposes of determining compliance with the ICNIRP basic restrictions.

9) *Question:* Why does ICNIRP not recommend higher basic restrictions or reference levels on exposure to ELF fields when exposures are of short duration?

Answer: The basic restrictions for ELF fields are based on established adverse effects on the central nervous system with a safety factor included. Such acute effects are essentially instantaneous, and it is ICNIRP's view that there is no scientific justification to modify the basic restrictions for exposures of short duration.

10) *Question:* Is the basic restriction of 10 mA m^{-2} based only on the threshold for acute effects in the central nervous system, or does it apply to other tissues in the trunk of the body?

Answer: The basic restriction of 10 mA m^{-2} is intended to protect against acute exposure effects on central nervous system tissues in the head and trunk of the body, with a safety factor of 10. ICNIRP recognizes that this basic restriction may permit higher current densities in body tissues other than the central nervous system under the same exposure conditions.

11) *Question:* Why are there no averaging times for induced and contact currents at low frequencies?

Answer: ICNIRP has not included time averaging or limitations on the time of exposure to fields at low frequencies because the known effects of induced and contact currents at those frequencies are acute phenomena involving a rapid response of the nervous system.

12) *Question:* Does ICNIRP intend to modify its guidelines at 300 GHz to remove the discontinuity that occurs at this frequency between the EMF guidelines and the recently published laser guidelines (ICNIRP. Guidelines on limits of exposure to laser radiation of wavelengths between 180 nm and 1,000 μm, Health Physics 71:804-819; 1997)?

Answer: ICNIRP recognizes that a discontinuity exists in the EMF guidelines at 300 GHz relative to the exposure limits at this frequency in the recently published laser radiation guidelines. This difficulty will be addressed by ICNIRP as more experimental evidence becomes available upon which to base a revision of the guidelines at this frequency. It should be noted that, at the present time, there are no sources of radiation at this frequency to which workers or members of the general public are exposed.

13) *Question:* What is the basis for the added safety factors used for basic restrictions and reference levels for the general public relative to workers?

Answer: The safety factors used by ICNIRP are conservative, and were selected for reasons given in the published guidelines (p. 508).

14) *Question:* Are there scientific data indicating a variation in sensitivity to EMF among individual workers or members of the general public?

Answer: ICNIRP is aware of scientific data on variations among individuals in electrical and thermal sensitivity, and in accord with conventional health protection principles, has applied safety factors that encompass a possible range of individual sensitivities to EMF.

15) *Question:* It is not clear how the EMF guidelines should be applied to exposure of the fetus, especially when the mother is at work. Would the mother be subject to the general public exposure guidelines, and in certain cases, have to cease work during pregnancy as a result?

Answer: ICNIRP recognizes that exposure of the fetus and pregnant mother may require evaluation on a case-by-case basis. Exposure of the fetus and pregnant mother is an issue that should be dealt with on the basis of either national policy or administrative rules established by individual employers.

16) *Question:* For devices utilized in both occupational and public settings, how is the user of the ICNIRP guidelines to decide which set of basic restrictions apply?

Answer: This decision is to be made on the basis of administrative policies established by the specific organization using the ICNIRP guidelines.

17) *Question:* Are farm workers in fields under powerlines expected to adhere to occupational or general public exposure guidelines?

Answer: ICNIRP recognizes that differences exist in national policies on occupational versus public exposures under this (and similar) conditions. In its guidelines ICNIRP has defined occupational and public exposures in general terms. However, for exposure situations such as the above, it is ICNIRP's opinion that authorities in each country should decide on whether occupational or general public guidelines are to be applied in accord with existing policies.

Apéndice B: Recomendación ICNIRP 2010

INTERNATIONAL COMMISSION ON NON-IONIZING RADIATION PROTECTION

ICNIRP GUIDELINES

FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC AND MAGNETIC FIELDS (1 Hz – 100 kHz)

PUBLISHED IN: **HEALTH PHYSICS 99(6):818-836; 2010**

ICNIRP PUBLICATION – 2010

GUIDELINES FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC AND MAGNETIC FIELDS (1 Hz TO 100 kHz)

International Commission on Non-Ionizing Radiation Protection*

INTRODUCTION

IN THIS document, guidelines are established for the protection of humans exposed to electric and magnetic fields in the low-frequency range of the electromagnetic spectrum. The general principles for the development of ICNIRP guidelines are published elsewhere (ICNIRP 2002). For the purpose of this document, the low-frequency range extends from 1 Hz to 100 kHz. Above 100 kHz, effects such as heating need to be considered, which are covered by other ICNIRP guidelines. However, in the frequency range from 100 kHz up to approximately 10 MHz protection from both, low frequency effects on the nervous system as well as high frequency effects need to be considered depending on exposure conditions. Therefore, some guidance in this document is extended to 10 MHz to cover the nervous system effects in this frequency range. Guidelines for static magnetic fields have been issued in a separate document (ICNIRP 2009). Guidelines applicable to movement-induced electric fields or time-varying magnetic fields up to 1 Hz will be published separately.

This publication replaces the low-frequency part of the 1998 guidelines (ICNIRP 1998). ICNIRP is currently revising the guidelines for the high-frequency portion of the spectrum (above 100 kHz).

SCOPE AND PURPOSE

The main objective of this publication is to establish guidelines for limiting exposure to electric and magnetic fields (EMF) that will provide protection against all established adverse health effects.

Studies on both direct and indirect effects of EMF have been assessed: direct effects result from direct interactions of fields with the body; indirect effects involve interactions with a conducting object where the electric potential of the object is different from that of the body. Results of laboratory and epidemiological studies, basic exposure assessment criteria, and reference levels for practical hazard assessment are discussed, and the guidelines presented here are applicable to both occupational and public exposure.

The restrictions in these guidelines were based on established evidence regarding acute effects; currently available knowledge indicates that adherence to these restrictions protect workers and members of the public from adverse health effects from exposure to low frequency EMF. The epidemiological and biological data concerning chronic conditions were carefully reviewed and it was concluded that there is no compelling evidence that they are causally related to low-frequency EMF exposure.

These guidelines do not address product performance standards, which are intended to limit EMF emissions from specific devices under specified test conditions, nor does the document deal with the techniques used to measure any of the physical quantities that characterize electric, magnetic and electromagnetic fields. Comprehensive descriptions of instrumentation and measurement techniques for accurately determining such physical quantities may be found elsewhere (IEC 2004, 2005a; IEEE 1994, 2008).

Compliance with the present guidelines may not necessarily preclude interference with, or effects on, medical devices such as metallic prostheses, cardiac pacemakers and implanted defibrillators and cochlear implants. Interference with pacemakers may occur at levels below the recommended reference levels. Advice on avoiding these problems is beyond the scope of the present document but is available elsewhere (IEC 2005b).

These guidelines will be periodically revised and updated as advances are made in the scientific knowledge concerning any aspect relevant for limiting exposure of low frequency time-varying electric and magnetic fields.

QUANTITIES AND UNITS

Whereas electric fields are associated only with the presence of electric charge, magnetic fields are the result

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of the physical movement of electric charge (electric current). An electric field, E, exerts a force on an electric charge and is expressed in volts per meter (V m^{-1}). Similarly, magnetic fields can exert physical forces on electric charges, if such charges are in motion and/or the magnetic field varies with time. Electric and magnetic fields have both magnitude and direction (i.e., they are vectors). A magnetic field can be specified in two ways—as magnetic flux density, B, expressed in tesla (T), or as magnetic field strength, H, expressed in ampere per meter (A m^{-1}). The two quantities are related by the expression:

$$\boldsymbol{B} = \mu \boldsymbol{H} \tag{1}$$

where μ is the constant of proportionality (the magnetic permeability); in vacuum and air, as well as in non-magnetic (including biological) materials, μ has the value $4\pi \times 10^{-7}$ when expressed in Henry per meter (H m^{-1}). Thus, in describing a magnetic field for protection purposes, only one of the quantities B or H needs to be specified.

Exposure to time-varying EMF results in internal electric fields and in body currents and energy absorption in tissues that depend on the coupling mechanisms and the frequency involved. The internal electric field E_i and current density J are related by Ohm's Law:

$$\boldsymbol{J} = \sigma \boldsymbol{E}_i \tag{2}$$

where σ is the electrical conductivity of the medium. The dosimetric quantities used in these guidelines are as follows:

- electric field E_i; and
- Current I.

A general summary of EMF and dosimetric quantities and units used in these guidelines is provided in Table 1.

SCIENTIFIC BASIS FOR LIMITING EXPOSURE

These guidelines for limiting exposure have been developed following a thorough review of the published scientific literature. Well established criteria were used to evaluate the scientific validity of the methodology, results and conclusions of reported findings. Only effects for which there was reliable scientific evidence were used as the basis for the exposure restrictions.

Biological effects of exposure to low frequency electromagnetic fields have been reviewed by the International Agency for Research on Cancer (IARC), ICNIRP, and the World Health Organization (WHO) (IARC 2002; ICNIRP 2003a; WHO 2007a) and national expert groups. Those publications provided the scientific basis for these guidelines.

As detailed below, the basis for the guidelines is two-fold: Exposure to low-frequency electric fields may cause well-defined biological responses, ranging from perception to annoyance, through surface electric-charge effects. In addition, the only well established effects in volunteers exposed to low frequency magnetic fields are the stimulation of central and peripheral nervous tissues and the induction in the retina of phosphenes, a perception of faint flickering light in the periphery of the visual field. The retina is part of the CNS and is regarded as an appropriate, albeit conservative, model for induced electric field effects on CNS neuronal circuitry in general.

In view of the uncertainty inherent in the scientific data, reduction factors have been applied in establishing the exposure guidelines. For details see ICNIRP 2002.

Table 1. Quantities and corresponding SI units used in these guidelines.

Quantity	Symbol	Unit
Conductivity	σ	Siemens per meter (S m^{-1})
Current	I	Ampere (A)
Current density	J	Ampere per square meter (A m^{-2})
Frequency	f	Hertz (Hz)
Electric field strength	E	Volt per meter (V m^{-1})
Magnetic field strength	H	Ampere per meter (A m^{-1})
Magnetic flux density	B	Tesla (T)
Magnetic permeability	μ	Henry per meter (H m^{-1})
Permittivity	ε	Farad per meter (F m^{-1})

Coupling mechanisms between fields and the body

Human and animal bodies significantly perturb the spatial distribution of a low frequency electric field. At low frequencies, the body is a good conductor, and the perturbed field lines external to the body are nearly perpendicular to the body surface. Oscillating charges are induced on the surface of the exposed body and these produce currents inside the body. Key features of dosimetry for exposure of humans to low frequency electric fields include:

- the electric field induced inside the body is considerably smaller than the external electric field, e.g., five to six orders of magnitude at 50–60 Hz;
- for a given external electric field, the strongest fields are induced when the human body is in perfect contact with the ground through the feet (electrically grounded), and the weakest induced fields are for the body insulated from the ground (in "free space");
- the total current flowing in a body in perfect contact with ground is determined by the body size and shape (including posture) rather than tissue conductivity;
- the distribution of induced currents across the various organs and tissues is determined by the conductivity of those tissues; and

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- there is also an indirect effect, where the current in the body is produced by contact with a conductive object located in an electric field.

For magnetic fields, the permeability of tissue is the same as that of air, so the field in tissue is the same as the external field. Human and animal bodies do not significantly perturb the field. The main interaction of magnetic fields is the Faraday induction of electric fields and associated currents in the tissues. Electric fields may also be induced by movement in a static magnetic field. Key features of dosimetry for exposure of humans to low frequency magnetic fields include:

- for a given magnetic field strength and orientation, higher electric fields are induced in the bodies of larger people because the possible conduction loops are larger;
- the induced electric field and current depend on the orientation of the external magnetic field to the body. Generally induced fields in the body are greatest when the field is aligned from the front to the back of the body, but for some organs the highest values are for different field alignments;
- the weakest electric fields are induced by a magnetic field oriented along the principal body axis; and
- the distribution of the induced electric field is affected by the conductivity of the various organs and tissues.

Conclusions from the current scientific literature

Neurobehavior. Exposure to low-frequency electric fields causes well-defined biological responses, ranging from perception to annoyance, through surface electric-charge effects (Reilly 1998, 1999). Thresholds for direct perception by the most sensitive 10% of volunteers at 50–60 Hz ranged between 2 and 5 kV m^{-1} and 5% found 15–20 kV m^{-1} annoying. The spark discharge from a person to ground is found to be painful to 7% of volunteers in a field of 5 kV m^{-1}, whereas it would be painful to about 50% in a 10 kV m^{-1} field. Thresholds for the spark discharge from a charged object through a grounded person depend on the size of the object and therefore require individual assessment.

The responsiveness of electrically excitable nerve and muscle tissue to electric stimuli including those induced by exposure to low-frequency EMFs has been well established for many years (e.g., Reilly 2002; Saunders and Jefferys 2007). Myelinated nerve fibers of the human peripheral nervous system have been estimated to have a minimum threshold value of around 6 V_{peak} m^{-1} (Reilly 1998, 2002), based on theoretical calculation using a nerve model. However, peripheral nerve stimulation induced during volunteer exposure to the switched gradient magnetic fields of magnetic resonance (MR) systems suggested that the threshold for perception may be as low as about 2 V m^{-1} (Nyenhuis et al. 2001), based on calculations using a homogeneous human phantom model. A more accurate calculation of the electric fields induced in the tissues of a heterogeneous human model based on data from the above MR study has been carried out by So et al. (2004). These authors estimated the minimum threshold for peripheral nerve stimulation of between about 4–6 V m^{-1}, based on the assumption that stimulation took place in the skin or subcutaneous fat. With stronger stimuli, discomfort and then pain ensue; the lowest percentile for intolerable stimulation is approximately 20% above the median threshold for perception (ICNIRP 2004). Myelinated nerve fibers of the central nervous system (CNS) can be stimulated by electric fields induced during transcranial magnetic stimulation (TMS); the pulsed fields induced in cortical tissue during TMS are quite high (>100 V $m^{-1}{}_{peak}$), although theoretical calculation suggests that minimum stimulation threshold values may be as low as ~10 V $m^{-1}{}_{peak}$ (Reilly 1998, 2002). For both sets of nerves, thresholds rise above around 1–3 kHz due to the progressively shorter time available for the accumulation of electric charge on the nerve membrane and below about 10 Hz due to the accommodation of a nerve to a slowly depolarizing stimulus.†

Muscle cells are in general less sensitive to direct stimulation than nerve tissue (Reilly 1998). Cardiac muscle tissue deserves particular attention because aberrant function is potentially life-threatening: however, ventricular fibrillation thresholds exceed those for cardiac muscle stimulation by a factor of 50 or more (Reilly 2002), although this drops considerably if the heart is repeatedly excited during the vulnerable period of the cardiac cycle. Thresholds rise above about 120 Hz due to the much longer time-constant of muscle fibers compared with myelinated nerves.

The most robustly established effect of electric fields below the threshold for direct nerve or muscle excitation is the induction of magnetic phosphenes, the perception of faint flickering light in the periphery of the visual field, in the retinas of volunteers exposed to low frequency magnetic fields. The minimum threshold flux density is around 5 mT at 20 Hz, rising at higher and lower frequencies. In these studies, the phosphenes are thought to result from the interaction of the induced electric field with electrically excitable cells in the retina. This is formed as an outgrowth of the forebrain and can

† Accommodation does not occur for example in response to the low-frequency component of trapezoid or rectangular pulses with quick rise-times but low repetition frequencies such as those found in the switched gradient fields of MR systems.

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be considered a good but conservative model of processes that occur in CNS tissue in general (Attwell 2003). The threshold for induced electric field strengths in the retina has been estimated to lie between about 50 and 100 mV m^{-1} at 20 Hz, rising at higher and lower frequencies (Saunders and Jefferys 2007) although there is considerable uncertainty attached to these values.

The integrative properties of the nervous tissue of the CNS may render it, and therefore functions such as cognitive processes like memory, sensitive to the effects of these physiologically weak electric fields. Saunders and Jefferys (2002) suggested that the electrical polarization of neurons in the CNS by such weak electric fields might enhance the synchronization of active groups of neurons and affect the recruitment of adjacent non-active neurons, thereby influencing overall nerve cell excitability and activity. *In vitro* evidence from studies using brain slices suggests that minimum thresholds for these effects lie below frequencies of ~100 Hz and may be as low as 100 mV m^{-1} (Saunders and Jefferys 2007).

Two research groups have investigated the effects of weak electric fields applied directly to the head via electrodes[‡] on brain electrical activity and function in humans. One group (Kanai et al. 2008) reported that stimulation of the visual cortex induced the perception of cortical phosphenes (similar in appearance to phosphenes induced in the retina) when the stimulus frequency was characteristic for visual cortical activity either in dark conditions (around 10 Hz) or in light conditions (around 20 Hz) but not at higher or lower frequencies. The other group (Pogosyan et al. 2009) applied a 20 Hz signal to the motor cortex of volunteers during the performance of a visuo-motor task and found a small but statistically significant slowing of hand movement during task performance, which was consistent with an increased synchronization of 20 Hz motor cortex activity. No effect was seen at a lower stimulus frequency. In summary, both groups of authors found that 10–20 Hz electric fields, above the threshold for retinal phosphenes, can interact with ongoing rhythmic electrical activity in the visual and motor cortices and slightly affect visual processing and motor co-ordination, carrying the implication that 10–20 Hz EMF-induced electric fields of sufficient magnitude may have similar effects.

However, the evidence for other neurobehavioral effects on brain electrical activity, cognition, sleep, and mood in volunteers exposed to low frequency EMFs is much less clear (Cook et al. 2002, 2006; Crasson 2003; ICNIRP 2003a; Barth et al. 2010). Generally, such studies have been carried out at exposure levels at or below about 1–2 mT; i.e., below those required to induce the effects described above, and have produced evidence of subtle and transitory effects at most. The conditions necessary to elicit such responses are not well defined at present.

Some people claim to be hypersensitive to EMFs in general. However, the evidence from double-blind provocation studies suggests that the reported symptoms are unrelated to EMF exposure (Rubin et al. 2005; WHO 2007a).

There is only inconsistent and inconclusive evidence that exposure to low-frequency electric and magnetic fields causes depressive symptoms or suicide (WHO 2007a).

In animals, the possibility that exposure to low frequency fields may affect neurobehavioral functions has been explored from a number of perspectives using a range of exposure conditions. Few effects have been established. There is convincing evidence that low-frequency electric fields can be detected by animals, most likely as a result of surface charge effects, and may elicit transient arousal or mild stress. Other possible field-dependent changes are less well defined (WHO 2007a).

Thus, the perception of surface electric charge, the direct stimulation of nerve and muscle tissue and the induction of retinal phosphenes are well established and can serve as a basis for guidance. In addition, there is also indirect scientific evidence that brain functions such as visual processing and motor co-ordination can be transiently affected by induced electric fields. However, the evidence from other neurobehavioral research in volunteers exposed to low frequency electric and magnetic fields is not sufficiently reliable to provide a basis for human exposure limits.

Neuroendocrine system. The results of volunteer studies as well as residential and occupational epidemiological studies suggest that the neuroendocrine system is not adversely affected by exposure to 50–60 Hz electric or magnetic fields. This applies particularly to circulating levels of specific hormones, including melatonin released by the pineal gland, and to a number of hormones involved in the control of body metabolism and physiology released by the pituitary gland. Most laboratory studies of the effects of 50–60 Hz exposure on night-time melatonin levels in volunteers found no effect when care was taken to control possible confounding (WHO 2007a).

From the large number of animal studies investigating the effects of 50–60 Hz electric and magnetic fields on rat pineal and serum melatonin levels, some reported

[‡] Transcranial AC stimulation or tACS is applied at levels below local skin perception thresholds.

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that exposure resulted in night-time suppression of melatonin, while other studies did not. In seasonally breeding animals, the evidence for an effect of exposure to 50–60 Hz fields on melatonin levels and melatonin-dependent reproductive status is predominantly negative (ICNIRP 2003a; WHO 2007a). No convincing effect on melatonin levels has been seen in a study of non-human primates chronically exposed to 50–60 Hz fields.

No consistent effects have been seen in the stress-related hormones of the pituitary-adrenal axis in a variety of mammalian species, with the possible exception of short-lived stress following the onset of low frequency electric-field exposure at levels high enough to be perceived (ICNIRP 2003a; WHO 2007a). Similarly, while few studies have been carried out, mostly negative or inconsistent effects have been seen in the levels of growth hormone and hormones involved in controlling metabolic activity or associated with the control of reproduction and sexual development.

Overall, these data do not indicate that low frequency electric and/or magnetic fields affect the neuroendocrine system in a way that would have an adverse impact on human health.

Neurodegenerative disorders. It has been hypothesized that exposure to low frequency fields is associated with several neurodegenerative diseases. For Parkinson's disease and multiple sclerosis the number of studies has been small and there is no evidence for an association between low frequency exposure and these diseases. For Alzheimer's disease and amyotrophic lateral sclerosis (ALS) more studies have been published. Some of these reports suggest that people employed in electrical occupations might have an increased risk for ALS (Kheifets et al. 2009). So far, no biological mechanism has been established which can explain this association, although it could have arisen because of confounders related to electrical occupations, such as electric shocks. Furthermore, studies using more sophisticated exposure assessment methods, e.g., job-exposure matrices, have generally not observed increased risks (Kheifets et al. 2009). For Alzheimer's disease, results are inconsistent. Strongest associations have been found in clinic based studies with a large potential for selection bias, but increased risks have also been observed in some, but not all, population based studies. Subgroup analyses within studies strengthen the impression of inconsistent data (Kheifets et al. 2009). Statistical heterogeneity between study results speaks against pooling of available results, although such attempts have been made (Garcia et al. 2008). In addition, there is some evidence for publication bias. Control of potential confounding from other occupational exposures has generally not been made. So far only one residential study is available, indicating an increased risk for Alzheimer's disease after long-term exposure, but based on very small numbers of cases (Huss et al. 2009).

The studies investigating the association between low frequency exposure and Alzheimer's disease are inconsistent. Overall, the evidence for the association between low frequency exposure and Alzheimer's disease and ALS is inconclusive.

Cardiovascular disorders. Experimental studies of both short-term and long-term exposure indicate that, while electric shock is an obvious health hazard, other hazardous cardiovascular effects associated with low frequency fields are unlikely to occur at exposure levels commonly encountered environmentally or occupationally (WHO 2007a). Though various cardiovascular changes have been reported in the literature, the majority of effects are small, and the results have not been consistent within or between studies (McNamee et al. 2009). Most of the studies of cardiovascular disease morbidity and mortality have shown no association with exposure (Kheifets et al. 2007). Whether a specific association exists between exposure and altered autonomic control of the heart remains speculative. Overall, the evidence does not suggest an association between low frequency exposure and cardiovascular diseases.

Reproduction and development. Overall, epidemiological studies have not shown an association between human adverse reproductive outcomes and maternal or paternal exposure to low frequency fields. There is some limited evidence for increased risk of miscarriage associated with maternal magnetic field exposure, but this reported association has not been found in other studies and overall the evidence for such an association is poor.

Exposures to low frequency electric fields of up to 150 kV m^{-1} have been evaluated in several mammalian species, including studies with large group sizes and exposure over several generations; the results consistently show no adverse developmental effects (ICNIRP 2003a; WHO 2007a).

Low frequency magnetic field exposure of mammals does not result in gross external, visceral or skeletal malformations using fields up to 20 mT (Juutilainen 2003, 2005; WHO 2007a). Overall, the evidence for an association between low frequency and developmental and reproductive effects is very weak.

Cancer. A considerable number of epidemiological reports, carried out particularly during the 1980's and 90's, indicated that long term exposure to 50–60 Hz magnetic fields, orders of magnitude below the limits of

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the 1998 ICNIRP exposure guidelines might be associated with cancer. While the first studies looked at childhood cancer in relation to magnetic fields, later research also investigated adult cancers. In general, the initially observed associations between 50–60 Hz magnetic fields and various cancers were not confirmed in studies designed to see whether the initial findings could be replicated. However, for childhood leukemia the situation is different. The research that followed the first study has suggested that there may be a weak association between the higher levels of exposure to residential 50–60 Hz magnetic fields and childhood leukemia risk, although it is unclear whether it is causal: a combination of selection bias, some degree of confounding and chance could explain the results (WHO 2007a). Two pooled analyses (Ahlbom et al. 2000; Greenland et al. 2000) indicate that an excess risk may exist for average exposures exceeding 0.3–0.4 μT, although the authors of those analyses cautioned strongly that their results cannot be interpreted as showing a causal relationship between magnetic fields and childhood leukemia.

At the same time, no biophysical mechanism has been identified and the experimental results from the animal and cellular laboratory studies do not support the notion that exposure to 50–60 Hz magnetic fields is a cause of childhood leukemia.

It should be noted that there is currently no adequate animal model of the most common form of childhood leukemia, acute lymphoblastic leukemia. Most studies report no effect of 50–60 Hz magnetic fields on leukemia or lymphoma in rodent models (ICNIRP 2003a; WHO 2007a). Several large-scale long-term studies in rodents have not shown any consistent increase in any type of cancer, including hematopoietic, mammary, brain, and skin tumors.

A substantial number of studies have examined the effects of 50–60 Hz magnetic fields on chemically-induced mammary tumors in rats (ICNIRP 2003a; WHO 2007a). Inconsistent results were obtained that may be due in whole or in part to differences in experimental protocols, such as the use of specific sub-strains. Most studies on the effects of 50–60 Hz magnetic field exposure on chemically-induced or radiation-induced leukemia/lymphoma models were negative. Studies of pre-neoplastic liver lesions, chemically-induced skin tumors, and brain tumors reported predominantly negative results.

Generally, studies of the effects of low frequency field exposure of cells have shown no induction of genotoxicity at fields below 50 mT (Crumpton and Collins 2004; WHO 2007a). Overall, in contrast to the epidemiological evidence of an association between childhood leukemia and prolonged exposure to power frequency magnetic fields, the animal cancer data, particularly those from large-scale lifetime studies, are almost universally negative. The data from cellular studies are generally supportive of the animal studies, though more equivocal.

Rationale for these recommended low frequency guidelines

ICNIRP addresses acute and chronic health effects and considers recent dosimetric developments in this guidance.

Acute effects. There are a number of well established acute effects of exposure to low-frequency EMFs on the nervous system: the direct stimulation of nerve and muscle tissue and the induction of retinal phosphenes. There is also indirect scientific evidence that brain functions such as visual processing and motor co-ordination can be transiently affected by induced electric fields. All these effects have thresholds below which they do not occur and can be avoided by meeting appropriate basic restrictions on electric fields induced in the body.

Following the recommendations made concerning guidelines on limits of exposure to static magnetic fields (ICNIRP 2009), ICNIRP considers that there are occupational circumstances where, with appropriate advice and training, it is reasonable for workers voluntarily and knowingly to experience transient effects such as retinal phosphenes and possible minor changes in some brain functions, since they are not believed to result in long-term or pathological health effects. Exposure of all parts of the body in these circumstances should be limited in order to avoid peripheral and central myelinated nerve stimulation. ICNIRP notes the relatively narrow margin between peripheral nerve perception and pain thresholds; see above. For both types of nerves, thresholds rise above around 1–3 kHz due to the very short membrane time-constants resulting from myelination, and below about 10 Hz due to the accommodation to a slowly depolarizing stimulus.

Avoiding retinal phosphenes should protect against any possible effects on brain function. Phosphene thresholds are a minimum around 20 Hz and rise rapidly at higher and lower frequencies, intersecting with the thresholds for peripheral and central nerve stimulation at which point limits on peripheral nerve stimulation should apply. For workers who are not trained and who may be unaware and not in control of their exposure status the basic restriction is set at the phosphene threshold in order to avoid these transient but potentially disturbing effects of exposure. For members of the public, a reduction factor of 5 is applied to the phosphene threshold.

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Exposure to low-frequency electric fields causes well-defined biological responses through surface electric-charge effects. Prevention of the painful effects of surface electric charge induced on the body by such exposure are addressed by the reference levels.

Chronic effects. The literature on chronic effects of low frequency fields has been evaluated in detail by individual scientists and scientific panels. WHO's cancer research institute, IARC (International Agency for Research on Cancer), evaluated low frequency magnetic fields in 2002 and classified them in category 2 B, which translates to "possibly carcinogenic to humans." The basis for this classification was the epidemiologic results on childhood leukemia.

It is the view of ICNIRP that the currently existing scientific evidence that prolonged exposure to low frequency magnetic fields is causally related with an increased risk of childhood leukemia is too weak to form the basis for exposure guidelines. In particular, if the relationship is not causal, then no benefit to health will accrue from reducing exposure.

Dosimetry. Historically, magnetic field models assumed that the body has a homogeneous and isotropic conductivity and applied simple circular conductive loop models to estimate induced currents in different organs and body regions. Electric fields induced by time varying electric and magnetic fields were computed by using simple homogeneous ellipsoid models. In recent years, more realistic calculations based on anatomically and electrically refined heterogeneous models (Xi and Stuchly 1994; Dimbylow 2005, 2006; Bahr et al. 2007) resulted in a much better knowledge of internal electric fields in the body from exposure to electric and magnetic fields.

The most useful dosimetric results for the purpose of these guidelines have been obtained from high resolution calculations of induced electric field with voxel sizes below 4 mm (Dimbylow 2005; Bahr et al. 2007; Hirata et al. 2009; Nagaoka et al. 2004). The maximum electric field is induced in the body when the external fields are homogeneous and directed parallel to the body axis (E-field) or perpendicular (H-field). According to those calculations, the maximum local peak electric field induced by a 50 Hz magnetic field in the brain is approximately 23–33 mV m^{-1} per mT, depending on field orientation and body model. There is no conversion factor for peripheral nerve tissue available at present. Therefore, the skin, which contains peripheral nerve endings, was chosen as a worst-case target tissue. The electric field induced in the skin by such a field is approximately 20–60 mV m^{-1} per mT. The maximum local electric field induced by a 50 Hz electric field in the brain is approximately 1.7–2.6 mV m^{-1} per kV m^{-1}, while in the skin it is approximately 12–33 mV m^{-1} per kV m^{-1}.

In view of the uncertainties in the available dosimetry as well as the influence of body parameters in the derivation of reference levels, ICNIRP is taking a conservative approach in deriving reference levels from the basic restrictions.

GUIDELINES FOR LIMITING EMF EXPOSURE

Separate guidance is given for occupational exposures and exposure of the general public. Occupational exposure in these guidelines refers to adults exposed to time-varying electric, and magnetic fields from 1 Hz to 10 MHz at their workplaces, generally under known conditions, and as a result of performing their regular or assigned job activities. By contrast, the term general population refers to individuals of all ages and of varying health status which might increase the variability of the individual susceptibilities. In many cases, members of the public are unaware of their exposure to EMF. These considerations underlie the adoption of more stringent exposure restrictions for the public than for workers while they are occupationally exposed.

Addressing scientific uncertainty

All scientific data and their interpretation are subject to some degree of uncertainty. Examples are methodological variability and inter-individual, inter-species, and inter-strain differences. Such uncertainties in knowledge are compensated for by reduction factors.

There is, however, insufficient information on all sources of uncertainty to provide a rigorous basis for establishing reduction factors over the whole frequency range and for all modulation patterns. Therefore, the degree to which caution is applied in the interpretation of the available database and in defining reduction factors is to a large extent a matter of expert judgment.

Basic restrictions and reference levels

Limitations of exposure that are based on the physical quantity or quantities directly related to the established health effects are termed basic restrictions. In this guideline, the physical quantity used to specify the basic restrictions on exposure to EMF is the internal electric field strength E_i, as it is the electric field that affects nerve cells and other electrically sensitive cells.

The internal electric field strength is difficult to assess. Therefore, for practical exposure assessment purposes, reference levels of exposure are provided. Most

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reference levels are derived from relevant basic restrictions using measurement and/or computational techniques but some address perception (electric field) and adverse indirect effects of exposure to EMF. The derived quantities are electric field strength (E), magnetic field strength (H), magnetic flux density (B) and currents flowing through the limbs (I_L). The quantity that addresses indirect effects is the contact current (I_C). In any particular exposure situation, measured or calculated values of any of these quantities can be compared with the appropriate reference level. Compliance with the reference level will ensure compliance with the relevant basic restriction. If the measured or calculated value exceeds the reference level, it does not necessarily follow that the basic restriction will be exceeded. However, whenever a reference level is exceeded it is necessary to test compliance with the relevant basic restriction and to determine whether additional protective measures are necessary.

BASIC RESTRICTIONS

The main objective of this publication is to establish guidelines for limiting EMF exposure that will provide protection against adverse health effects. As noted above, the risks come from transient nervous system responses including peripheral (PNS) and central nerve stimulation (CNS), the induction of retinal phosphenes and possible effects on some aspects of brain function.

In view of the considerations above for frequencies in the range 10 Hz to 25 Hz, occupational exposure should be limited to fields that induce electric field strengths in CNS tissue of the head (i.e., the brain and retina) of less than 50 mV m^{-1} in order to avoid the induction of retinal phosphenes. These restrictions should also prevent any possible transient effects on brain function. These effects are not considered to be adverse health effects; however, ICNIRP recognizes that they may be disturbing in some occupational circumstances and should be avoided but no additional reduction factor is applied. Phosphene thresholds rise rapidly at higher and lower frequencies, intersecting with the thresholds for peripheral and central myelinated nerve stimulation at 400 Hz. At frequencies above 400 Hz, limits on peripheral nerve stimulation apply in all parts of the body.

Exposure in controlled environments, where workers are informed about the possible transient effects of such exposure, should be limited to fields that induce electric fields in the head and body of less than 800 mV m^{-1} in order to avoid peripheral and central myelinated nerve stimulation. A reduction factor of 5 has been applied to a stimulation threshold of 4 V m^{-1} in order to account for the uncertainties described above. Such restrictions rise above 3 kHz.

For the general public for CNS tissue of the head a reduction factor of 5 is applied, giving a basic restriction of 10 mV m^{-1} between 10 and 25 Hz. Above and below these values, the basic restrictions rise. At 1,000 Hz it intersects with basic restrictions that protect against peripheral and central myelinated nerve stimulation. Here, the reduction factor of 10 results in a basic restriction of 400 mV m^{-1}, which should be applied to the tissues of all parts of the body.

The basic restrictions are presented in Table 2 and Fig. 1.

Time averaging

ICNIRP recommends that the restrictions on internal electric fields induced by electric or magnetic fields including transient or very short-term peak fields be regarded as instantaneous values which should not be time averaged (see also section on non-sinusoidal exposure).

Spatial averaging of induced electric field

When restricting adverse effects of induced electric fields to nerve cells and networks, it is important to define the distance or volume over which the local induced electric field must be averaged. As a practical compromise, satisfying requirements for a sound biological basis and computational constraints, ICNIRP recommends determining the induced electric field as a vector average of the electric field in a small contiguous tissue volume of $2 \times 2 \times 2$ mm^3. For a specific tissue, the 99th percentile value of the electric field is the relevant value to be compared with the basic restriction.

Table 2. Basic restrictions for human exposure to time-varying electric and magnetic fields.

Exposure characteristic	Frequency range	Internal electric field (V m^{-1})
Occupational exposure		
CNS tissue of the head	1–10 Hz	0.5/f
	10 Hz–25 Hz	0.05
	25 Hz–400 Hz	2×10^{-3}f
	400 Hz–3 kHz	0.8
	3 kHz–10 MHz	2.7×10^{-4}f
All tissues of head and body	1 Hz–3 kHz	0.8
	3 kHz–10 MHz	2.7×10^{-4}f
General public exposure		
CNS tissue of the head	1–10 Hz	0.1/f
	10 Hz–25 Hz	0.01
	25 Hz–1000 Hz	4×10^{-4}f
	1000 Hz–3 kHz	0.4
	3 kHz–10 MHz	1.35×10^{-4}f
All tissues of head and body	1 Hz–3 kHz	0.4
	3 kHz–10 MHz	1.35×10^{-4}f

Notes:
- f is the frequency in Hz.
- All values are rms.
- In the frequency range above 100 kHz, RF specific basic restrictions need to be considered additionally.

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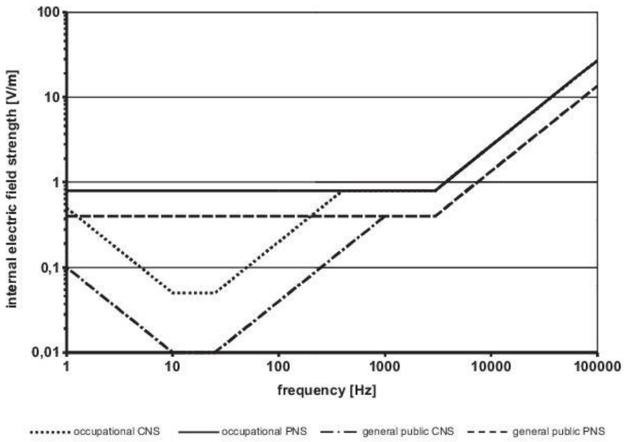

Fig. 1. Basic restrictions for general public and occupational exposure in terms of internal electric field strength concerning CNS and PNS effects.

Basically the electric field effects on neurons and other electrically excitable cells are local effects, but there are electrophysiological and practical dosimetric factors that constrain the minimum volume or distance. The major physical factor disturbing the function of neurons and neuronal networks is the voltage produced by the induced electric field over the membrane of the cell. For isolated nerve fibers aligned along the direction of the electric field (maximum coupling) this voltage is integrated from the electric field over the electrotonic distance varying from 2 to 7 millimeters for invertebrate nerves (Reilly 1998; Reilly and Diamant 2003). For myelinated nerve cells a good assumption for the integration distance is approximately 2 mm, which is the maximum inter-nodal distance between the nodes of Ranvier. These distances are relevant when considering stimulation thresholds to isolated nerve cells. In the case of sub-threshold weak electric field effects, such as retinal phosphenes, the collective "network" effect of numerous interacting nerve cells must be taken into account. The threshold of the effect is considerably lower than the stimulation threshold of isolated nerve cells, which is due to summation and integration of small, induced voltages in the synapses. It has been suggested that the averaging volume for the induced electric field should be based on minimum of 1,000 interacting cells, which is approximately 1 mm^3 in most nerve tissue (Jefferys 1994). Hence, a biologically reasonable averaging distance might extend from 1 to 7 mm. From a practical point of view, it is difficult to achieve satisfactory accuracy in the millimeter resolution computation of the induced electric field, and even more difficult to measure it. Maximal values in one voxel in a specific tissue are prone to large stair-casing errors associated with sharp corners of the cubical voxel. A solution to obtain more stable peak approximations is based on choosing for the peak value a value representing the 99th percentile value of the induced field in a specific tissue. From the biological point of view however, this is a somewhat arbitrary choice because the peak value depends on the resolution. Another option for the spatial averaging is to define the local electric field as an average in a small volume or along a line segment (Reilly and Diamant 2003).

As a general rule the averaging volume should not extend beyond the boundary of the tissue except for tissues such as the retina and skin, which are too thin to cover the whole averaging cube. For the skin the same averaging volume of $2 \times 2 \times 2$ mm^3 can be assumed, and it may extend to the subcutaneous tissue. For the retina the averaging volume may extend to the tissues in front and behind it.

REFERENCE LEVELS

The reference levels are obtained from the basic restrictions by mathematical modeling using published data (Dimbylow 2005, 2006). They are calculated for the condition of maximum coupling of the field to the exposed individual, thereby providing maximum protection. Frequency dependence and dosimetric uncertainties were taken into account. The reference levels presented consider two distinct effects and approximate a combination of the induced electric fields in the brain,

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relevant for CNS effects, and the induced electric fields in non-CNS tissues anywhere in the body, relevant for PNS effects (i.e., at 50 Hz, the factor used to convert the basic restriction for CNS effects to an external magnetic field exposure is 33 V m^{-1} per T, and for PNS effect 60 V m^{-1} per T. An additional reduction factor of 3 was applied to these calculated values to allow for dosimetric uncertainty).

In addition, the electric field reference level for occupational exposure up to 25 Hz includes a sufficient margin to prevent stimulation effects from contact currents under most practical conditions. Between 25 Hz and 10 MHz the reference levels are based on the basic restriction on induced electric fields only and might thus not provide a sufficient margin to prevent stimulation effects from contact currents under all possible conditions in that frequency band.

The electric field reference levels for general public exposure up to 10 MHz prevent adverse indirect effects (shocks and burns) for more than 90% of exposed individuals. In addition, the electric field reference levels for general public exposure up to 50 Hz include a sufficient margin to prevent surface electric-charge effects such as perception in most people.

Tables 3 and 4 summarize the reference levels for occupational and general public exposure, respectively, and the reference levels are illustrated in Figs. 2 and 3. The reference levels assume an exposure by a uniform (homogeneous) field with respect to the spatial extension of the human body.

Spatial averaging of external electric and magnetic fields

Reference levels have been determined for the exposure conditions where the variation of the electric or magnetic field over the space occupied by the body is relatively small. In most cases, however, the distance to the source of the field is so close that the distribution of the field is non-uniform or localized to a small part of the body. In these cases the measurement of the maximum field strength in the position of space occupied by the body always results in a safe, albeit very conservative exposure assessment.

For a very localized source with a distance of a few centimeters from the body, the only realistic option for the exposure assessment is to determine dosimetrically the induced electric field, case by case. When the distance exceeds 20 cm, the distribution of the field becomes less localized but is still non-uniform, in which case it is possible to determine the spatial average along the body or part of it (Stuchly and Dawson 2002; Jokela 2007). The spatial average should not exceed the reference level. The local exposure may exceed the reference level but with an important provision that the basic restriction shall not be exceeded. It is the task of standardization bodies to give further guidance on the specific exposure situations where the spatial averaging can be applied. This guidance shall be based on well established dosimetry. The standardization bodies also may derive new reference levels for special types of non-uniform exposure.

Table 3. Reference levels for occupational exposure to time-varying electric and magnetic fields (unperturbed rms values).

Frequency range	E-field strength E (kV m^{-1})	Magnetic field strength H (A m^{-1})	Magnetic flux density B (T)
1 Hz–8 Hz	20	$1.63 \times 10^5/f^2$	$0.2/f^2$
8 Hz–25 Hz	20	$2 \times 10^4/f$	$2.5 \times 10^{-2}/f$
25 Hz–300 Hz	$5 \times 10^2/f$	8×10^2	1×10^{-3}
300 Hz–3 kHz	$5 \times 10^2/f$	$2.4 \times 10^5/f$	$0.3/f$
3 kHz–10 MHz	1.7×10^{-1}	80	1×10^{-4}

Notes:
- f in Hz.
- See separate sections below for advice on non sinusoidal and multiple frequency exposure.
- To prevent indirect effects especially in high electric fields see chapter on "Protective measures."
- In the frequency range above 100 kHz, RF specific reference levels need to be considered additionally.

Table 4. Reference levels for general public exposure to time-varying electric and magnetic fields (unperturbed rms values).

Frequency range	E-field strength E (kV m^{-1})	Magnetic field strength H (A m^{-1})	Magnetic flux density B (T)
1 Hz–8 Hz	5	$3.2 \times 10^4/f^2$	$4 \times 10^{-2}/f^2$
8 Hz–25 Hz	5	$4 \times 10^3/f$	$5 \times 10^{-3}/f$
25 Hz–50 Hz	5	1.6×10^2	2×10^{-4}
50 Hz–400 Hz	$2.5 \times 10^2/f$	1.6×10^2	2×10^{-4}
400 Hz–3 kHz	$2.5 \times 10^2/f$	$6.4 \times 10^4/f$	$8 \times 10^{-2}/f$
3 kHz–10 MHz	8.3×10^{-2}	21	2.7×10^{-5}

Notes:
- f in Hz.
- See separate sections below for advice on non sinusoidal and multiple frequency exposure.
- In the frequency range above 100 kHz, RF specific reference levels need to be considered additionally.

Additivity of exposure to electric and magnetic fields

Each of the external electric and magnetic field induces an electric field component, which add vectorially in the tissue. In the case of the exposure analysis based on the external electric and magnetic fields, a conservative approach would be to assume that both the electrically and magnetically induced field components attain the maximum value in the same critical point at the same phase. This would imply that the exposures to the external electric and magnetic fields are additive (Cech et al. 2008). Such situations, however, are judged to be very

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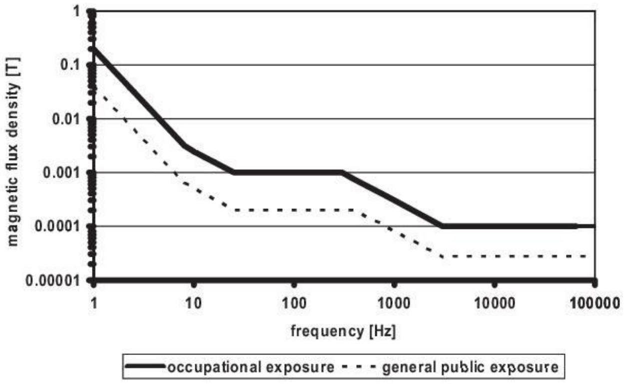

Fig. 2. Reference levels for exposure to time varying magnetic fields (compare Tables 3 and 4).

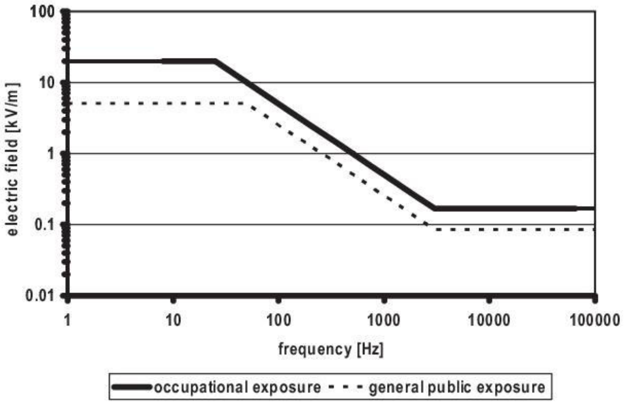

Fig. 3. Reference levels for exposure to time varying electric fields (compare Tables 3 and 4).

infrequent taking into account the great difference in the distribution of the electrically and magnetically induced electric fields.

REFERENCE LEVELS FOR CONTACT CURRENTS

Up to 10 MHz reference levels for contact current are given for which caution must be exercised to avoid shock and burn hazards. The point contact reference levels are presented in Table 5. Since the threshold contact currents that elicit biological responses in children are approximately one-half of those for adult men, the reference levels for contact current for the general public are set lower by a factor of 2 than the values for occupational exposure. It should be noted that the reference levels are not intended to prevent perception but to avoid painful shocks. Perception of contact current is not *per se* hazardous but could be considered as annoyance. Prevention of excess contact currents is possible by technical means.

Table 5. Reference levels for time-varying contact currents from conductive objects.

Exposure characteristics	Frequency range	Maximum contact current (mA)
Occupational exposure	Up to 2.5 kHz	1.0
	2.5–100 kHz	0.4*f*
	100 kHz–10 MHz	40
General public exposure	Up to 2.5 kHz	0.5
	2.5–100 kHz	0.2*f*
	100 kHz–10 MHz	20

Note: *f* is the frequency in kHz.

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SIMULTANEOUS EXPOSURE TO MULTIPLE FREQUENCY FIELDS

It is important to determine whether, in situations of simultaneous exposure to fields of different frequencies, these exposures are additive in their effects. The formulae below apply to relevant frequencies under practical exposure situations. For electrical stimulation, relevant for frequencies up to 10 MHz, internal electric fields should be added according to

$$\sum_{j=1\,Hz}^{10\,MHz} \frac{E_{i,j}}{E_{L,j}} \leq 1 \qquad (3)$$

where $E_{i,j}$ is the internal electric field strength induced at frequency j, and $E_{L,j}$ is the induced electric field strength restriction at frequency j as given in Table 2.

For practical application of the basic restrictions, the following criteria regarding reference levels of field strengths should be applied:

$$\sum_{j=1\,Hz}^{10\,MHz} \frac{E_j}{E_{R,j}} \leq 1 \qquad (4)$$

and

$$\sum_{j=1\,Hz}^{10\,MHz} \frac{H_j}{H_{R,j}} \leq 1 \qquad (5)$$

where

E_j = the electric field strength at frequency j;
$E_{R,j}$ = the electric field strength reference level at frequency j as given in Tables 3 and 4;
H_j = is the magnetic field strength at frequency j;
$H_{R,j}$ = the magnetic field strength reference level at frequency j as given in Tables 3 and 4.

For limb current and contact current, respectively, the following requirements should be applied:

$$\sum_{j=1\,Hz}^{10\,MHz} \frac{I_j}{I_{L,j}} \leq 1 \qquad (6)$$

where I_j is the contact current component at frequency j, and $I_{L,j}$ is the reference level of the contact current at frequency j as given in Table 5.

NON SINUSOIDAL EXPOSURE

At low frequencies below 100 kHz the electric and particularly magnetic fields are in most cases distorted by harmonic components distributed over a large frequency band. Consequently, the waveforms of the fields show complex, often pulsed, patterns. It is always possible to decompose such a field to discrete spectral components by using, e.g., Fourier Transformation techniques (FT) and applying the multiple frequency rule described above. This procedure is based on the assumption that the spectral components add in phase, i.e., all maxima coincide at the same time and results in a sharp peak. This is a realistic assumption when the number of spectral components is limited and their phases are not coherent, i.e., they vary randomly. For fixed coherent phases the assumption may be unnecessarily conservative. Additionally, sampling and windowing in FT spectral analysis may create spurious frequencies, which may artificially increase the linearly summed exposure ratio.

An alternative option to the spectral method is to weight the external electric and magnetic fields, induced electric field and induced current with a filter function which is related to the basic restriction or reference level (ICNIRP 2003b; Jokela 2000). In the case of a broadband field consisting of harmonic components the restriction imposed by the filtering can be presented mathematically as

$$\left| \sum_i \frac{A_i}{EL_i} \cos(2\pi f_i t + \theta_i + \varphi_i) \right| \leq 1, \qquad (7)$$

where t is time and EL_i is the exposure limit at the ith harmonic frequency f_i, where A_i, θ_i, φ_i, are the amplitudes of the field, phase angles of the field and phase angles of the filter at the harmonic frequencies. Except the phase angles, the equation is similar to the summation eqns (3), (4), and (5). More guidance on the practical implementation of the weighting (determination of the weighted peak exposure) is given in the informative annex (Appendix).

PROTECTIVE MEASURES

ICNIRP notes that protection of people exposed to electric and magnetic fields could be ensured by compliance with all aspects of these guidelines.

Measures for the protection of workers include engineering and administrative controls, and personal protection programs. Appropriate protective measures must be implemented when exposure in the workplace results in the basic restrictions being exceeded. As a first step, engineering controls should be undertaken wherever possible to reduce device emissions of fields to acceptable levels. Such controls include good safety design and, where necessary, the use of interlocks or similar health protection mechanisms.

Administrative controls, such as limitations on access and the use of audible and visible warnings, should be used in conjunction with engineering controls. Personal protection measures, such as protective clothing, though useful in certain circumstances, should be regarded as a last resort to ensure the safety of the worker,

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and priority should be given to engineering and administrative controls wherever possible. Furthermore, when such items as insulated gloves are used to protect individuals from shock, the basic restrictions must not be exceeded, since the insulation protects only against indirect effects of the fields.

With the exception of protective clothing and other personal protection, the same measures can be applied to the general public whenever there is a possibility that the general public reference levels might be exceeded. It is also essential to establish and implement rules that will prevent

- interference with medical electronic equipment and devices (including cardiac pacemakers);
- detonation of electro-explosive devices (detonators); and
- fires and explosions resulting from ignition of flammable materials by sparks caused by induced fields, contact currents, or spark discharges.

CONSIDERATIONS REGARDING POSSIBLE LONG-TERM EFFECTS

As noted above, epidemiological studies have consistently found that everyday chronic low-intensity (above 0.3–0.4 μT) power frequency magnetic field exposure is associated with an increased risk of childhood leukemia. IARC has classified such fields as possibly carcinogenic. However, a causal relationship between magnetic fields and childhood leukemia has not been established nor have any other long term effects been established. The absence of established causality means that this effect cannot be addressed in the basic restrictions. However, risk management advice, including considerations on precautionary measures, has been given by WHO (2007a and b) and other entities.

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R. Matthes, Vice-Chairperson since 2008 (Germany)
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E. Breitbart until 2008 (Germany)
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APPENDIX

Informative annex

Determination of the weighted peak exposure. The weighting may be implemented by computing first the spectrum of the waveform and then applying eqn (7). In many applications, however, it is more convenient to use analog or digital filtering of the waveform in the time domain. The gain of the filter (ratio of the output to the input signal) should vary as a function of frequency in direct proportion to the exposure limit $G = EL(f_{ref})/EL(f)$, where EL is the limit at frequency f and f_{ref} is an arbitrary reference frequency from 1 Hz to 100 kHz. The peak value of the filtered waveform should not exceed the exposure limit (basic restriction or reference level) converted to the peak (amplitude) value at the reference frequency. Table 6 shows an example of the derived peak limits. In addition to the amplitude physical filters always influence on the phase of the field, which changes the peak value of the filtered field. As shown in Figs. 1, 2, and 3 the limits are divided to the frequency ranges where the limit varies directly proportional to $1/f^2$, $1/f$, f^0 (constant), or f. On the $1/f^2$, $1/f$, f^0, and f ranges the phase angle of the filter φ_i (see eqn 7) is 180, 90, 0, and −90°, respectively. The weighting filter can be approximated with an electronic or digital filter where the attenuation should not deviate more than 3 dB and phase more than 90° from the exact piecewise linear frequency response. As an example, Fig. A1 shows the attenuation and phase as a function of frequency for the filter used for the weighting of the induced electric field. The approximate curves are based on a simple approximation with RC (resistor/capacitor) type filter function. The weighted peak approach can be used both for coherent and non-coherent fields. In the latter case the measurement time must be long enough to detect the worst case peak value with a reasonable probability. In the case of non-coherent fields, consisting of a few frequencies, the weighted peak approach is identical to the spectral summation.

Table 6. Derived peak limits for non-sinusoidal electric and magnetic fields. The reference frequency is 50 Hz.

	$E_{induced}$ (mV m^{-1}) Brain	body tissue	$E_{external}$ (V m^{-1})	B μT
Occupational	$\sqrt{2} \times 100$	$\sqrt{2} \times 800$	$\sqrt{2} \times 10{,}000$	$\sqrt{2} \times 1{,}000$
General public	$\sqrt{2} \times 20$	$\sqrt{2} \times 400$	$\sqrt{2} \times 5{,}000$	$\sqrt{2} \times 200$

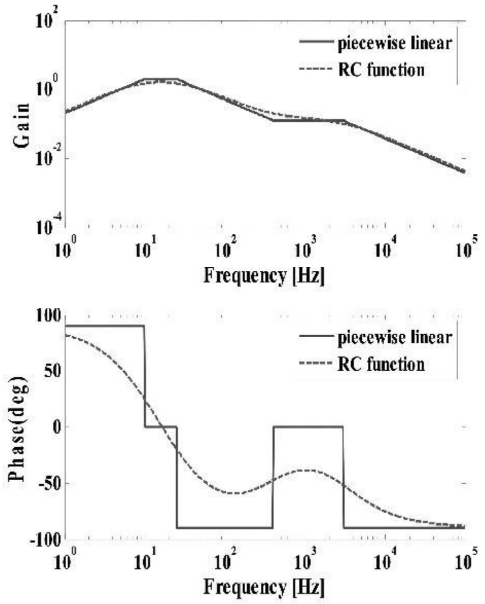

Fig. A1. Amplitude and phase response for the weighting of the induced electric field.

GLOSSARY

Adverse effect
An effect detrimental to the health of an individual due to exposure to an electric or magnetic field, or a contact current.

Averaging distance
The distance over which the *internal* electric field is averaged when determining compliance with basic restrictions.

Basic restrictions
Mandatory limitations on the quantities that closely match all known biophysical interaction mechanisms with tissue that may lead to adverse health effects.

Cancer
Diseases characterized by the uncontrolled and abnormal division of eukaryotic cells and by the spread of the disease (metastasis) to disparate sites in the organism.

Central nervous system (CNS)
The portion of the vertebrate nervous system consisting of the brain and spinal cord, but not including the peripheral nerves.

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Characteristics
Detailed physical properties of electric or magnetic fields such as the magnitude, frequency spectrum, polarization, modulation, etc.

Conductivity
A property of materials that determines the magnitude of the electric current density when an electric field is impressed on the material, expressed in units of siemens per meter (S m^{-1}); the inverse of resistivity.

Contact current
Current passed into a biological medium via a contacting electrode or other source of current.

Current density
A vector of which the integral over a given surface is equal to the current flowing through the surface; the mean density in a linear conductor is equal to the current divided by the cross-sectional area of the conductor. Expressed in ampere per square meter (A m^{-2}).

DC
Abbreviation for "direct current," but also used for to indicate constancy of fields, see "Static field."

Depolarization (cellular)
The reduction of the resting potential across a cellular membrane.

Direct effect
A biological effect resulting from direct interaction of EMF with biological structures.

Direct electro stimulation
Stimulation via the electric field within the biological medium induced by an external electric or magnetic field without direct contact with other conductors or spark discharges.

DNA (deoxyribonucleic acid)
A polymeric molecule consisting of deoxyribonucleotide building blocks that in a double-stranded, double-helical form is the genetic material of most organisms.

Dosimetry
Measurement, or determination by calculation, of internal electric field strength or induced current density or specific absorption (SA), or specific absorption rate (SAR), in humans or animals exposed to electromagnetic fields.

Electric field
A vector field E measured in volts per meter.

Electric field strength (*E*)
Force exerted by an electric field on an electric point charge, divided by the electric charge. Electric field strength is expressed in newton per coulomb or volts per meter (N/C = V/m).

Electromagnetic energy
The energy stored in an electromagnetic field. Expressed in joule (J).

Electromagnetic fields
The combination of electric and magnetic fields in the environment. This term is often confused with "electromagnetic radiation" and can therefore be misleading when used with extremely low frequencies for which the radiation is barely detectable.

Electro stimulation
Induction of a propagating action potential in excitable tissue by an applied electrical stimulus; electrical polarization of presynaptic processes leading to a change in post synaptic cell activity.

EMF
Electric and magnetic fields.

Established mechanism
A bioelectric mechanism having the following characteristics: (a) can be used to predict a biological effect in humans; (b) an explicit model can be made using equations or parametric relationships; (c) has been verified in humans, or animal data can be confidently extrapolated to humans; (d) is supported by strong evidence; and (e) is widely accepted among experts in the scientific community.

Exposure
That which occurs whenever a person is subject to the influence of a low frequency field or contact current.

Exposure, long-term
This term indicates exposure during a major part of the lifetime of the biological system involved; it may, therefore, vary from a few weeks to many years in duration.

Exposure assessment
The evaluation of a person's exposure by measurements, modeling, information about sources or other means.

Exposure metric
A single number that summarizes exposure to an electric and/or magnetic field. The metric is usually determined by a combination of the instrument's signal

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processing and the data analysis performed after the measurement.

Frequency
The number of sinusoidal cycles completed by electromagnetic waves in 1 second; usually expressed in hertz (Hz).

General public
The term General public refers to the entire population. It includes individuals of all ages, and of varying health status, and this will include particularly vulnerable groups or individuals such as the frail, elderly, pregnant workers, babies and young children.

General public exposure
All exposure to low frequency fields received by members of the general public. This definition excludes occupational exposure, and medical exposure.

Harmonic (frequency)
Frequencies that are integral multiples of the power frequency or some other reference frequency.

Heart rate
The measurement of the number of heartbeats per minute.

Hertz (Hz)
The unit for expressing frequency, (*f*). One hertz equals one cycle per second. 1 kHz = 1,000 Hz, 1 MHz = 1,000 kHz, 1 GHz = 1,000 MHz.

Induction
An electric or magnetic field in a conducting medium caused by the action of a time-varying external (environmental) electric or magnetic field.

Instantaneous
Adjective used to describe particular parameters that must be measured or evaluated over a very short time interval (typically 100 microseconds or less).

Let-go current
The threshold current level at which involuntary muscular contraction prevents release of a grip on an energized conductor.

Magnetic field
A vector quantity, H, specifies a magnetic field at any point in space, and is expressed in ampere per meter (A m^{-1}). See also magnetic flux density.

Magnetic field strength (*H*)
The magnitude of the magnetic field vector; expressed in units of ampere per meter (A/m).

Magnetic flux density (*B*)
A vector quantity that determines the force on a moving charge or charges (electric current). Magnetic flux density is expressed in tesla (T). One gauss (deprecated unit) equals 10^{-4} T.

Magnetophosphenes
The sensation of flashes of light caused by induced electric currents stimulating the retina.

Mean
The arithmetic average of a series of measurements or other data.

Median threshold
The threshold value within a statistical distribution at which 50% of subjects have greater thresholds and 50% have lesser thresholds.

Medical exposure
Exposure of a person to low frequency fields received as a patient undergoing medical diagnosis or recognized medical treatment, or as a volunteer in medical research.

Mutagen
A substance that is able to cause a mutation.

Mutation
Any detectable and heritable change in the genetic material not caused by genetic recombination.

Nerve
A bundle of axons.

Nerve fiber
A single nerve axon.

Neuron
A single cellular unit usually consisting of an axon, cell body, and dendritic tree.

Non-ionizing radiation (NIR)
Includes all radiations and fields of the electromagnetic spectrum that do not normally have sufficient energy to produce ionization in matter; characterized by energy per photon less than about 12 eV, which is equivalent to wavelengths greater than 100 nm, or frequencies lower than 3×10^{15} Hz.

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No uniform field
A field that is not constant in amplitude, direction, and relative phase over the dimensions of the body or body part under consideration. In the case of electric fields, the definition applies to an environmental field undisturbed by the presence of the body.

Occupational exposure
All exposure to EMF experienced by individuals as a result of performing their regular or assigned job activities.

Peripheral nerve
Nerve found outside the central nervous system and leading to and from the central nervous system.

Permeability
The scalar or tensor quantity whose product by the magnetic field strength is the magnetic flux density. Note: For isotropic media, the permeability is a scalar; for anisotropic media, a matrix. Synonym: absolute permeability. If the permeability of a material or medium is divided by the permeability of vacuum (magnetic constant) μ_0, the result is termed relative permeability (μ). Unit: henrys per meter (H m^{-1}).

Permittivity
A constant defining the influence of an isotropic medium on the forces of attraction or repulsion between electrified bodies, and expressed in farad per meter (F/m); *relative permittivity* is the permittivity of a material or medium divided by the permittivity of vacuum.

Phase duration (t_p)
The time between zero crossings of a waveform having zero mean. For a sine wave of frequency f, $t_p = 1/(2f)$. For an exponential waveform, t_p is interpreted as the duration measured from the waveform peak to a point at which it decays to 0.37 (e^{-1}) of its peak value.

Phosphene
Visual sensation caused by non-photic stimuli. Electro-phosphenes are induced by electric currents; magneto-phosphenes are induced magnetically.

Plasma membrane
Lipid bilayer that surrounds the cytoplasm of both animal and plant cells.

Polarization (cellular)
The electric potential formed across a cell membrane.

Power frequency
The frequency at which AC electricity is generated. For electric utilities, the power frequency is 60 Hz in North America, Brazil, and parts of Japan, and 50 Hz in much of the rest of the world.

Protein
One of a group of high-molecular weight, nitrogen-containing organic compounds of complex shape and composition.

Public exposure
All exposure to EMF experienced by members of the general public, excluding occupational exposure and exposure during medical procedures.

Radiofrequency (RF)
Electromagnetic energy with frequencies in the range 3 kHz to 300 GHz.

Reduction factor
Reduction of the effect threshold to compensate for various sources of uncertainty in the guideline setting process. Some examples of sources of uncertainty about exposure-effect threshold levels include the extrapolation of animal data to effects on humans, differences in the physiological reserves of different people with corresponding differences in tolerance, and statistical uncertainties (confidence limits) in the dose-response function. In ICNIRP's view, uncertainty in measurements used to implement the guidelines is a problem more appropriate to the functions of organizations responsible for the development of compliance methods. It is not considered in the setting of reduction factors by ICNIRP.

Reference levels
The rms and peak electric and magnetic fields and contact currents to which a person may be exposed without an adverse effect and with acceptable safety factors. The reference levels for electric and magnetic field exposure in this document may be exceeded if it can be demonstrated that the basic restrictions are not exceeded.

Thus, it is a practical or "surrogate" parameters that may be used for determining compliance with the Basic Restrictions.

Relative permeability
(Absolute) permeability (q.v.) divided by the permeability in vacuum. A value near one signifies that the material is only weakly magnetized by an external field.

Relative phase
The phase angle of a sinusoidal waveform relative to the phase angle of another waveform measured at a different point within the conductive medium or with respect to a stated reference waveform.

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Relative risk (RR)

The ratio of the disease rate in the group under study to that in a comparison group, with adjustments for confounding factors such as age, if necessary. For rare diseases, the relative risk is practically the same as the odds ratio.

Root mean square (rms)

The square root of the mean of the square of a time variant function, $F(t)$, over a specified time period from t_1 to t_2. It is derived by first squaring the function and then determining the mean value of the squares obtained, and taking the square root of that mean value, i.e.,

$$F_{\mathrm{rms}} = \sqrt{\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} [F(t)]^2 dt}. \quad \text{(A1)}$$

S.I.

Abbreviation for the International system of units.

Spatial peak

Term used to describe the highest level of a particular quantity averaged over a small mass or area in the human body.

Spark discharge

The transfer of current through an air gap requiring a voltage high enough to ionize the air, as opposed to direct contact with a source.

Static field

A field that does not vary with time. In most environments, electric and magnetic fields change with time, but their frequency spectrum has a component at 0 Hz. This "quasi-static" component of the field can be measured by averaging the oscillating signal over the sample time.

Tesla (T)

S.I. unit of magnetic flux density. 1 tesla = 10,000 gauss (q.v.).

Threshold

The level of a stimulus marking the boundary between a response and a no response.

Ventricular fibrillation

Arrhythmia of the ventricles of the heart characterized by rapid uncoordinated contractions.

Voxel

A three-dimensional computational element. In this standard used to represent animal and human tissues in dosimetry models.

Waveform

The variation of an electrical amplitude with time. Unless otherwise stated, in this standard the term *waveform* refers to values (or measurements) at sites within the biological medium.

Workers

See glossary term *Occupational exposure.*

■■

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Apéndice C: Hoja de especificaciones técnicas EFA- 300

5 Hz to 32 kHz

EFA-300 Field Analyzer

For Isotropic Measurement of Magnetic and Electric Fields

- **Evaluation of Field Exposure Compared to Major Standards and Guidances (selectable)**
- **Shaped Time Domain (STD) – an innovative technique for signal-shape-independent field measurements**
- **Fast Fourier Transform (FFT) Spectral Analysis**
- **Peak Value Measurement with Proper Phase**
- **Large-Capacity Data Storage**
- **Remote Control**

Applications

The EFA-300 is an ideal field analyzer for measuring magnetic and electric fields in the workplace and in public spaces. It is designed for professional users in the power industry, at municipal utilities, by insurers, and for health and safety professionals in industry. In the low frequency range, it handles virtually any required measurement, simply and precisely. This instrument provides field analysis using an FFT computation in addition to measuring magnetic and electric fields. The innovative STD mode opens up further application areas. With this new mode the measurement results for magnetic and electric field strength are displayed as a Percent of Standard, regardless of the signal shape. This mode enables fast and reliable measurement and evaluation of the typical fields where complex, non-sinusoidal signals are common, e.g., in industrial applications that use resistance welding. Resistance welding issues surface in the traditional 50/60 Hz systems as well as in the newer medium-frequency switching units.

Basic Operation

The EFA-300 has a built-in, isotropic, magnetic field probe. Optional external probes can be used to handle other applications. For example, an isotropic B-field probe with high sensitivity and a large (100 cm^2) cross-sectional area is available for the standardized measurement of dissimilar magnetic fields.

For measurements in hard-to-reach places, a miniature 3 cm diameter B-field "sniffer" probe is available.

The EFA-300 includes a cubic-shaped, isotropic, E-field module. This E-field module contains both the sensor and circuitry that allows it to be operated independent of the base unit. The base instrument, or a computer with the EFA-TS remote software, can be used to read results in real-time and control the functions of the module. In the data-logging mode, the E-field module can be operated independently. Stored data can be read and analyzed at a later date using a computer and the EFA-TS software. The major advantage of operating the E-field module remotely is that it greatly reduces the influence of the human body on the electric field you are trying to measure.

EFA-300 Field Analyzer

Operating Modes

Various standards and guidances take into account the fact that signal shape plays a major role in determining the workplace limit. For example, in Germany the employer's liability insurance association guideline on "Electromagnetic Fields" specifies different evaluation guidelines for different field shapes. Stationary sinusoidal and pulsed fields are differentiated. Occasionally both the RMS value and the peak value, (with proper phase) are critical for assessing exposure in the low-frequency range.

This new generation of equipment greatly simplifies the measurement process. Besides measuring the RMS and peak values with the classic filter technique, the EFA-300 includes the highly innovative mode known as STD (Shaped Time Domain). With this new mode, both instruments achieve a new standard in simple but reliable measurement, even in very complex environments. A standard's variation with frequency can be automatically taken into account and normalized. Field strength results are provided in a "Percent of Standard." Knowledge about the signal shape, frequency, or frequency-dependent limits is no longer needed.

For individual frequency and field strength analysis, a very fast FFT (Fast Fourier Transform) mode, which includes evaluation of harmonics, is available as an option.

Field Strength Mode

Selective and Broadband Field Strength Measurements

In many practical applications, such as proximity to high-voltage lines and transformer stations, this measurement is simple and produces accurate results. If the field under test has essentially a single frequency component, the broadband mode is the best choice. A broadband measurement of the magnetic field in the frequency range from 5 Hz to 32 kHz is made using the built-in isotropic probe. The Model EFA-300 can also be used to measure the electric field with the external, cube-shaped E-field module.

For more precise analysis or multi-frequency fields, band pass and band reject filters are available in the frequency range of 15 Hz to 2 kHz with user-editable filter lists. Operation is configured to allow fast switching between common settings, e.g., broadband and bandpass filter.

In broadband mode, the large, backlit display provides measurement and frequency results simultaneously.

Two plug-in, B-field, probes extend the range of possibilities. The small "sniffer" probe has a 3 cm diameter while the larger, more sensitive probe, has a 100 cm^2 cross-sectional area.

Users can choose between RMS and peak value measurement from less than 1 nT to 31.6 mT. The EFA-300 can also measure the E-field from less than 1 V/m to 100 kV/m.

STD (Shaped Time Domain) Evaluation Mode

Innovative Technique for Signal-Shape-Independent Field Measurements

In many situations, detailed knowledge of the field, test equipment and other auxiliary conditions are necessary to obtain insight into the degree of exposure when using traditional measurement equipment. Standardized evaluation entails complicated analysis. However, the new and innovative "Shaped Time Domain" technique simplifies the process.

The frequency dependency of standards is automatically incorporated when using shaped-frequency-response measurements. Suitable detectors are provided for measuring the RMS and peak values. The analysis takes into account the phase of the individual components.

The B- or E-field is measured over the entire frequency range up to 32 kHz in real time and displayed as a Percent of Standard.

STD analysis is not limited to specific signal shapes. Signals with one or more frequencies and pulsed signals are no problem. Pulsed signal measurements are possible since the time-domain limits (e.g., those specified for selected pulsed signals) can be directly converted into frequency-domain limits. Proper evaluation in a personal safety context is achieved quickly and reliably using the STD technique.

To evaluate the field, six limit curves (standards) are stored in the device. A simple download procedure can be used to update the instrument to cover new standards.

Spectrum FFT Mode (Optional)

Spectrum analysis considerably simplifies the process of quickly evaluating multi-frequency signals up to 32 kHz. All spectral components are evaluated at once.

To provide a spectrum, the signal curve versus time is recorded via the probe and converted into the frequency domain using a mathematical procedure known as "Fast Fourier Transform."

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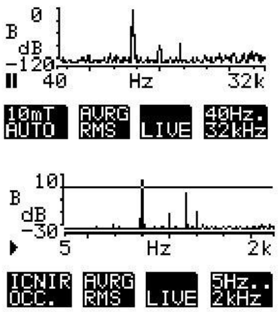


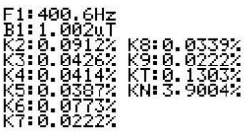
The EFA-300 is so powerful that even transient events ranging up to 2 kHz can be analyzed in real time.

Evaluation is supported by graphics to clearly show the frequency spectrum and by cursor functions with frequency and level indications. The RMS and peak values of the nine most significant frequency components are easy to read.

You can also use this mode to normalize the display to a given standard. The measured value is then displayed relative to its associated standard. In visual terms, the frequency-dependent standard becomes a straight line. This makes it easy to determine the relevancy of each spectral component.

Harmonic Analysis Mode

(Included with Spectrum FFT Mode)



This mode enables fast, convenient evaluation of the harmonic spectrum. A table lists the field strengths of the measured fundamental frequency along with up to 8 harmonics.

This feature is very useful for a "hands-off" verification of power quality ("Quality of Service") in addition to occupational safety applications.

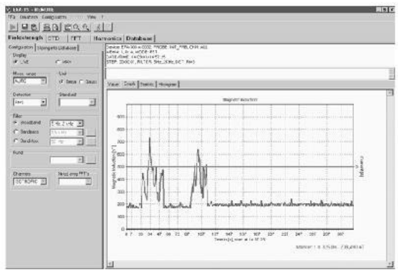
Remote And Data Analysis Software EFA-TS

This optional software is used to:

- Provide remote control of the field analyzer and data readout
- Download the data stored in the device
- Save acquired data on the computer
- Analyze the data and provide a graphic representation of the results to support the user in the preparation of measurement reports

FEATURES

- Windows® interface to configure the instrument and/or to control it remotely.
- Graphic representation of data stored in the internal memory of the instrument or in a file:
  - Line diagrams show field strength or Percent of Standard versus time. Can be used in real time.
  - Display of spectrum
  - Bar graph of harmonics
  - 2D-views with import possibility: background maps for Matrix-data sets
  - Graphic tools – zoom, marker, set-up for scale, color/ thickness of lines, etc.
- Additional Analysis Functions:
  - Statistics – mean and maximum values, histogram, and number of values over a defined threshold
  - Peak list for spectrums
- Export Functions
  - Data sets as ASCII-files
  - Graphic screen into the clipboard

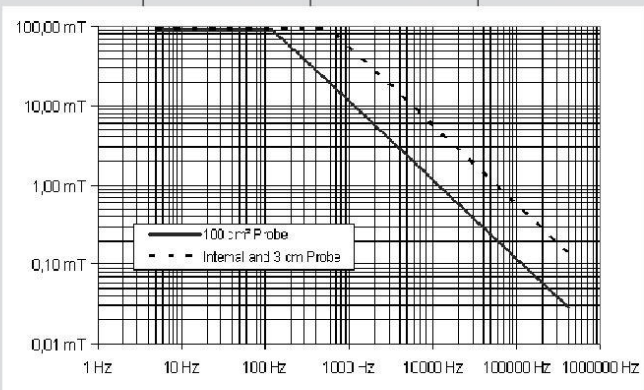


MINIMUM SYSTEM REQUIREMENTS

- Microsoft® Windows® 95 or Higher
- Windows NT® 4.0 or Higher
- Pentium Processor
- Min. 4 MB RAM
- Graphic card VGA 640/480, 256 colors
- CD-ROM

EFA-300 Field Analyzer

Specifications

		MAGNETIC (B-) FIELD 100 cm^2 Probe	Internal Probe	3 cm Probe	ELECTRIC (E-) FIELD
Sensor System		Coil (internal or external)			Plate Electrode
Measurement Axis, selectable		Tri-Axial (Isotropic) or Single Axis			
FIELD STRENGTH MODE					
Frequency Range	Broadband (+0/-3 dB), selectable	5 Hz to 2 kHz, 30 Hz to 2 kHz, 5 Hz to 32 kHz or 30 Hz to 32 kHz			
	Band Pass / Band Reject Filter, adjustable	15 Hz to 2 kHz (resolution 0.1 Hz)			
Detection, selectable		RMS (averaging time 1 sec.) Peak Value (proper phase)			
Measurement Range	Nominal	100 nT to 32 mT	100 nT to 32 mT	100 nT to 32 mT	10 V/m to 100 kV/m
	Damage Level (Peak)	91 mT[a] @ ≤125 Hz	91 mT[a] @ ≤625 Hz	91 mT[a] @ ≤625 Hz	280 kV/m
Damage Level (Peak)	Damage Level (Peak) [a] For magnetic field probes depending on frequency				
Noise Level (RSM), typical	Broadband, 30 Hz to 2 kHz	4 nT	100 nT	20 nT	0.7 V/m
	Broadband, 5 Hz to 32 kHz	10 nT	200 nT	50 nT	4.5 V/m
	Band Pass Filter, 50 Hz to 400 Hz	0.8 nT	25 nT	5 nT	0.14 V/m
Uncertainty, typical [b]	Broadband, 5 Hz to 2 kHz	±3% @ ≥40 nT	±5% @ ≥1 µT	±4% @ ≥200 nT	±3% @ ≥5 V/m
	Broadband, 5 Hz to 32 kHz	±3% @ ≥80 nT	±8% @ ≥2 µT	±5% @ ≥400 nT	±3% @ ≥40 V/m
	Band Pass Filter, 50 Hz to 400 Hz	±3% @ ≥10 nT	±5% @ ≥250 nT	±4% @ ≥50 nT	±3% @ ≥1 V/m

[a] The upper limit decreases linearly with increasing frequency above the mentioned frequency.

Overload limit for 100 cm^2 Probe = $\left(\frac{8000\ mT \cdot Hz}{Frequency}\right) \cdot \sqrt{2}$

Overload limit for 3 cm and internal Probe 100 cm^2 Probe = $\left(\frac{40000\ mT \cdot Hz}{Frequency}\right) \cdot \sqrt{2}$

[b] Uncertainty includes all partial uncertainties (absolute, linearity, frequency response, and isotropy) as well as temperature and humidity related deviations. Signal sinusoidal, level >10% of selected measurement range; additional uncertainties apply with the steep frequency band limits.

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		MAGNETIC (B-) FIELD			ELECTRIC (E-) FIELD
		100 cm² Probe	Internal Probe	3 cm Probe	
EXPOSURE STD MODE					
Frequency Range (+0/-3 dB)		5 Hz to 32 kHz			
Exposure Evaluation		Compared to Standards Stored in Meter [c]			
Measurement Range / Overload Limit		200%	200%	200%	200%
Noise Level, typical [d] (for ICNIRP Occupational)		<0.4%	<2%	<1%	<5%
Uncertainty, typical (percent of reading) [b]		±4%	±9%	±6%	±4%
SPECTRUM FFT / HARMONICS MODE (Optional)					
Frequency Range		5 Hz to 2 kHz 40 Hz to 32 kHz			
Fundamental Range (HARMONICS only)		10 Hz to 400 Hz 10 Hz to 10 kHz (Option, FFT 5 Hz-32 kHz)			
Resolution by Marker:	2 kHz Range	0.01 Hz			
	32 kHz Range	0.1 Hz			
Frequency Scale, selectable:	2 kHz Range	Full-Scale Logarithmic or 100 Hz Wide Linear Span			
	32 kHz Range	Full-Scale Logarithmic or 1000 Hz Wide Linear Span			
Detection, selectable		RMS, RMS Average, Peak Value or Vector Peak Value (at each single frequency, proper phase)			
Measurement Range		See FIELD STRENGTH MODE			
Noise/ Spurious Level (RSM), typical		See Table 1 (on next page)			
Uncertainty, by marker [b]		See FIELD STRENGTH MODE			
Results Scale, selectable		20 dB to 120 dB (logarithmic)			
Data Acquisition, (start/stop)	2 kHz Range	Continuous and Overlapping / Seamless			
	32 kHz Range	Continuous			
Window Length:	2 kHz Range	1.0 second			
	32 kHz Range	0.1 second			
Result Averaging, selectable	2 kHz Range	1, 2, 4, or 8 seconds			
	32 kHz Range	4, 8, 16, or 32 Spectra			
Graphical Display, selectable (SPECTRUM FFT only)		Result: Absolute or Normalized to Reference Limit of Selected Standard; Marker Displays 9 Highest Peaks within Selected Frequency Range			
Result List, tabular (HARMONICS only)		Result of 2^{nd} to 9^{th} Harmonic[e] and Total Distortion (with/within noise), Referenced to the Level of Fundamental Frequency			
MEASUREMENT DATA MEMORY (individual in B- and E- Field unit)					
Capacity, typical (dependent on setting)		3600 Single Values or 22 Spectral Analyses			
Control:	Field Strength & Exposure STD Modes	Manual or Sequence Timer or Sequence Spatial-Assigned			
	Spectrum FFT & Harmonics Modes	Manual Only			

[b] Uncertainty includes all partial uncertainties (absolute, linearity, frequency response, and isotropy) as well as temperature and humidity related deviations. Signal sinusoidal, level >10% of selected measurement range; additional uncertainties apply with the steep frequency band limits.

[c] Stored standards can be updated by software: e.g. ICNIRP: occupational, general public; BGV B11: Exp. (2 h/d), Exp. 1, Exp. 2; VDE 0848: draft

[d] Dependent on selected standard.

[e] Limited by selected frequency range

Electric and Magnetic Field Measurement

EFA-300 Field Analyzer

General Specifications

		B-FIELD UNIT	E-FIELD MODULE
Display		LCD Dot Matrix 128x64 Pixel with Backlight	Via B-Field Unit
Alarm, Adjustable Threshold		Acoustical, Optical	Via B-Field Unit
Current Documentation (Specific Modes Only)		Input of Prevailing and Reference Current Value; Storage with Measurement Value of Field	N/A
Interface (Remote Control, Data Memory)		Optical, Serial (RS-232)	
Operating Temperature Range		0°C to +50°C	
Humidity		<95% or <29 g/m³ Occasional Brief Condensation Tolerable	
Operating Interval, typical	Continuous Measurement	10 Hours	
	Programmed Sequence Time	24 Hours	
Calibration Interval, recommended		24 Months	
Battery		NiMH Batteries (5x C-cell), exchangeable	NiMH Batteries, built in
Dimensions, approximate		4.3 x 7.9 x 2.4 inches (110 x 200 x 60 mm)	4.1 x 4.1 x 4.1 inches (105 x 105 x 105 mm)
Weight, approximate		2.2 lbs. (1000 g)	2.2 lbs. (1000 g)

Table 1: Spectrum FFT Sensitivity (Noise / Spurious)

	MAGNETIC (B-) FIELD			ELECTRIC (E-) FIELD
	100 cm² Probe	Internal Probe	3 cm Probe	
2 kHz Range	<45 nT @ ≤48 Hz <4 nT @ >48 Hz <0.05 nT @ noise floor	<400 nT @ ≤48 Hz <42 nT @ >48 Hz <2 nT @ noise floor	<260 nT @ ≤48 Hz <23 nT @ >48 Hz <0.2 nT @ noise floor	<0.3 V/m @ ≤48 Hz <0.1 V/m @ >48 Hz <0.02 V/m @ noise floor
32 kHz Range	<2 nT @ <200 Hz <0.3 nT @ 200 Hz to 20 kHz <0.6 nT @ >20 kHz <0.07 nT @ noise floor	<22 nT @ <200 Hz <11 nT @ 200 Hz to 20 kHz <11 nT @ >20 kHz <1.5 nT @ noise floor	<10 nT @ <200 Hz <2 nT @ 200 Hz to 20 kHz <3 nT @ >20 kHz <0.3 nT @ noise floor	<0.1 V/m @ ≤20 kHz <3 V/m @ >20 kHz <0.05V/m @ noise floor

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Calibration Certificate

Narda Safety Test Solutions hereby certifies that the object referenced to this certificate has been calibrated by qualified personnel using Narda's approved procedures. The calibration was carried out in accordance with a certified quality management system which conformed to ISO 9001.

OBJECT	**Broadband Field Meter NBM-550**
MANUFACTURER	Narda Safety Test Solutions GmbH
PART NUMBER (P/N)	**2401/01B**
SERIAL NUMBER (S/N)	**H-0396**
CUSTOMER	
CALIBRATION DATE (YYYY-MM-DD)	2018-01-31
RESULT ASSESSMENT	within specifications
AMBIENT CONDITIONS	Temperature: (23 ± 3) °C Relative humidity: (20 to 60) %
CALIBRATION PROCEDURE	2401-8700-00A

ISSUE DATE: 2018-01-31
(YYYY-MM-DD)

CALIBRATED BY
Ludwig

AUTHORIZED SIGNATORY

MANAGEMENT SYSTEM

DQS

Certified by DQS according to ISO 9001:2008 (Reg.-No. 099379 QM08)

This calibration certificate may not be reproduced other than in full except with the permission of the issuing laboratory. Calibration certificates without signature are not valid.

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Method of Measurement

The device under test (DUT) represents a three-channel voltage meter offering high accuracy and high resolution. The DUT is calibrated by applying a known DC voltage to each of the inputs.

Uncertainty of Measurement

The measurement uncertainty stated in this document is the expanded uncertainty with a coverage factor of 2 (corresponding, in the case of normal distribution, to a confidence probability of 95 %).

The uncertainty analysis for this calibration was done in accordance with the ISO/TAG-Guide (Guide to the expression of uncertainty in measurement). The measurement uncertainties are derived from contributions from the measurement of power, reflection, attenuation and frequency, mismatch, stability of instrumentation and repeatability of handling.

This statement of uncertainty applies to the measured values only and does not include effects like temperature response and long term stability of the calibrated device.

Traceability of Measuring Equipment

The calibration results are traceable to SI-units according to ISO/IEC 17025. Physical units, which are not included in the list of accredited measured quantities such as field strength or power density, are traced to the basic units via approved measurement and computational methods.

The equipment used for this calibration is traceable to the reference listed below and the traceability is guaranteed by ISO 9001 Narda internal procedure.

Reference- / Working- Standard	Manufacturer	Model	Serial Number	Certificate Number	Cal Due Date	Trace
Digital Multimeter	Agilent	34401A	MY47052911	1-8659117607-1	2019-02	UKAS 0147

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Results

Voltage display uncertainty

Channel	Input voltage applied	Specified voltage display	Meas. Uncertainty	Meas. voltage display
X	2.400 V	(2.376+/-0.024) V	+/-0.007 V	2.370 V
Y	2.400 V	(2.376+/-0.024) V	+/-0.007 V	2.370 V
Z	2.400 V	(2.376+/-0.024) V	+/-0.007 V	2.370 V

Note: Because of an internal voltage divider the nominal indication is 2.376 V.

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17035 Cisano sul Neva (SV)
Tel.: +39 0182 58641 Fax: +39 02 586400

CERTIFICATE OF CALIBRATION
Certificato di taratura

Number 70700
Numero

Item *Oggetto*: Electric and Magnetic field Probe - Analyzer

Manufacturer *Costruttore*: Narda S.T.S. / PMM

Model *Modello*: EHP50F

Serial number *Matricola*: 100WY70700

Calibration procedure *Procedura di taratura*: Internal procedure PTP 09-31

Date(s) of measurements *Data(e) delle misure*: 11.01.2018

Result of calibration *Risultato della taratura*: Measurements results within specifications

This calibration certificate documents the traceability to national/international standards, which realise the physical units of measurements according to the International System of Units (SI). Verification of traceability is guaranteed by mentioning used equipment included in the measurement chain. This equipment includes reference standard directly traceable to (inter)national standard (accuracy rating A) and working standard calibrated by the calibration laboratory of Narda Safety Test Solutions (accuracy rating B) by means of reference standard A or by other calibration laboratory.
The measurement uncertainties stated in this document are estimated at the level of twice the standard deviation (corresponding, in the case of normal distribution, to a confidence level of about 95%). The uncertainties are calculated in conformity to the ISO Guide (Guide to the expression of uncertainty in measurement).The metrological confirmation system for the measuring equipment used is in compliance with ISO 10012-1. The applied quality system is certified to UNI EN ISO 9001.
Questo certificato di taratura documenta la tracciabilità a campioni primari nazionali o internazionali i quali realizzano la riferibilità alle unità fisiche del Sistema Internazionale delle Unità (SI). La verifica della tracciabilità è garantita elencando gli strumenti presenti nella catena di misura.La catena di riferibilità metrologica fa riferimento a campioni di prima linea direttamente riferiti a standard (inter)nazionali (classe A), di seconda linea, tarati nel laboratorio metrologico della Narda Safety Test Solutions con riferibilità ai campioni di prima linea oppure tarati da Enti esterni accreditati (classe B).
Le incertezze di misura dichiarate in questo documento sono espresse come due volte lo scarto tipo (corrispondente, nel caso di distribuzione normale, a un livello di confidenza di circa 95%). Le incertezze di misura sono calcolate in riferimento alla guida ISO. La conferma metrologica della strumentazione usata è conforme alla ISO 10012-1. Il sistema di qualità è certificato ISO 9001.

COMPANY WITH QUALITY MANAGEMENT SYSTEM CERTIFIED BY DNV
= ISO 9001:2008 =

Date of issue *Data di emissione*	Measure operator *Operatore misure*	Person responsible *Responsabile*
17.01.2018	F. Ferrari	G. Basso

This calibration certificate may not be reproduced other than in full. Calibration certificate without signature are not valid. The user is recommended to have the object recalibrated at appropriate intervals.
La riproduzione del presente documento è ammessa in copia conforme integrale. Il certificato non è valido in assenza di firma. All'utente dello strumento è raccomandata la ricalibrazione nell'appropriato intervallo di tempo.

The calibration was carried out at an ambient temperature of (23 ± 3)°C and at a relative humidity of (50 +10/-20)%.

Calibration method

The magnetic calibration was set up with the probe in a region of uniform magnetic field at the centre of a calibrated Helmholtz coil system. The magnetic flux density is calculated from the current flowing in the coil. The current waveform was sinusoidal. The current in the Helmholtz coil system was adjusted to produce a series of indicated magnetic flux densities on the instrument at various frequencies. The calibration procedure agrees with the indication of IEC 61786 "Measurement of low frequency magnetic and electric fields with regard to exposure of human beings- Special requirements for instruments"
The instrument readings were recorded and the actual values of magnetic flux density were calculated from the measured currents.
The magnetic correction factor (CF) is defined as rapport between actual and indicated magnetic flux density.

$$CF = \frac{Bo}{Bmis}$$

where Bo is the applied magnetic flux density and Bmis is the indicated magnetic flux density

For the electric calibration the probe is positioned inside a big TEM cell (section 1.8x1.8 mete
For each measurement, the input voltage was adjusted so that the field strength was set to a specified reading on the monitor.
The actual field strength, at the plane of reference of the probe was then determined and the correction factor calculated using the following definition.

$$CF = \frac{Eo}{Emis}$$

where Eo is the applied field strength and Emis is the indicated field strength

The correction factor data are permanently stored in the internal EEPROM.

Calibration equipment and traceability

ID Number	Description	Manufacturer	Model	Trace
PMM 391	Digital multimeter	Agilent	34401A	/UKAS
CMR 169	Electric and Magnetic ref. Probe	Narda	EHP50C-REF	/INRIM
CMR 090	Standard resistor	Narda	PMM BSD250	/NPL
CMR 095	Current Trasformer	Frer	AP10-1TAC010	/INRIM
CMR 001	TEM Cell	Narda	1818	/Narda
CMR 020	Helmholtz coil	Narda	HCSS001	/Narda

Uncertainty of measurements

The statement of uncertainty (see first page) does not make any implication or include any estimation as to the long term stablity of the calibrated monitor. The relative expanded uncertainty result are given below

E field	3% at 50 Hz
	5.3% other frequencies
H field	2% at 50 Hz with 100µT range
	3.5% at 50 Hz with 10mT range
	3% other frequencies

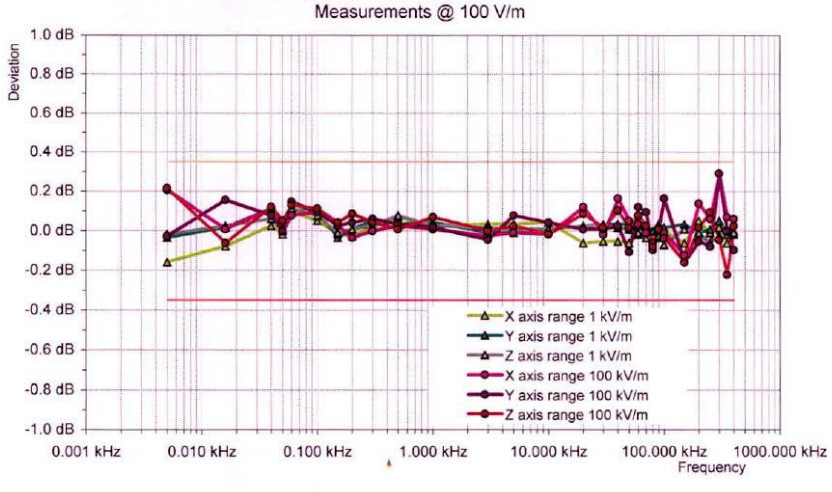
Results

The results of measurements in the following pages were obtained after calibration data storing and indicates the residual of the reciprocal CF.
The results given on the tables were obtained with the axis aligned at the electric vector for electric measurements and with axis concatenated at the magnetic flux density for magnetic mesurements
The shown limits of the EHP50F specification in the diagrams are in orange.

Electric field Frequency response for each axis at nominal field of 100 V/m.
The instrument was set as electric field measure with 100 Hz span up to the frequency of 100 Hz, 200 Hz span up to the frequency of 200 Hz, 500 Hz span up to the frequency of 500 Hz, 1 kHz up to 1000 Hz, 10 kHz up to 10 kHz, 100 kHz up to 100 kHz and span 400 kHz for frequency over 100 kHz.

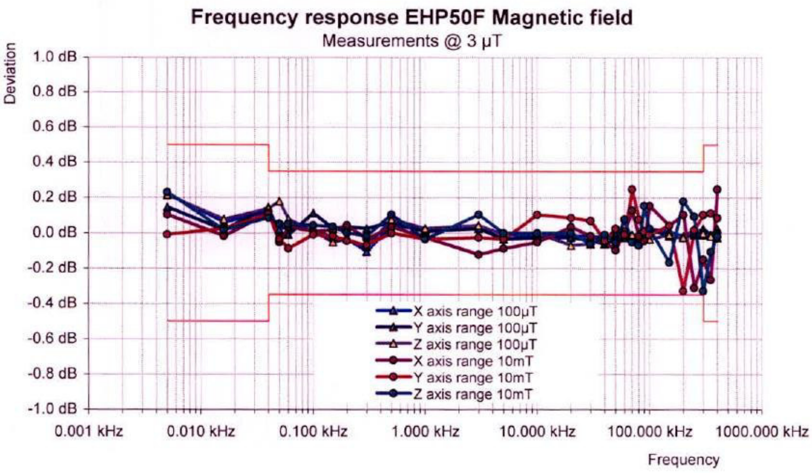
Freq. (kHz)	Deviation with 1kV/m range			Deviation with 100 kV/m range		
	X axis (dB)	Y axis (dB)	Z axis (dB)	X axis (dB)	Y axis (dB)	Z axis (dB)
0.005	-0.16	-0.03	-0.02	0.21	-0.03	0.21
0.016	-0.08	0.02	0.03	0.01	0.15	-0.06
0.04	0.03	0.11	0.06	0.11	0.08	0.12
0.05	-0.02	0.01	0.00	0.00	0.00	0.05
0.06	0.10	0.10	0.11	0.08	0.15	0.13
0.10	0.05	0.10	0.08	0.10	0.10	0.11
0.15	-0.02	-0.03	-0.01	0.03	0.03	0.04
0.20	-0.03	0.01	0.01	-0.03	0.04	0.09
0.30	0.02	0.05	0.03	0.00	0.06	0.04
0.50	0.07	0.03	0.08	0.03	0.03	0.01
1.0	0.03	0.04	0.03	0.01	0.02	0.07
3.0	0.03	-0.01	0.02	-0.03	-0.04	0.00
5.0	0.03	-0.01	0.01	-0.01	0.08	0.03
10.0	0.04	0.01	0.01	-0.02	0.04	-0.02
20.0	-0.06	0.03	0.03	0.12	0.01	0.09
30.0	-0.05	0.03	0.03	-0.02	0.01	0.02
40.0	-0.05	0.03	0.02	0.16	0.03	0.10
50.0	-0.06	0.03	0.01	0.05	-0.10	0.02
60.0	-0.02	0.03	-0.01	0.03	0.12	0.08
70.0	0.03	0.02	-0.03	-0.01	0.10	0.03
80.0	0.00	0.00	-0.06	-0.06	-0.10	-0.08
90.0	-0.03	-0.03	0.03	0.02	0.01	0.01
100.0	0.00	0.02	-0.07	-0.01	0.16	-0.03
150.0	-0.06	0.03	0.01	-0.12	-0.16	-0.16
200.0	0.05	-0.01	-0.01	0.14	-0.05	0.02
250.0	-0.01	0.01	-0.06	0.06	-0.08	0.10
300.0	0.02	0.05	-0.03	0.29	0.29	-0.04
350.0	-0.06	-0.02	0.01	0.07	0.00	-0.22
400.0	-0.02	0.00	-0.01	0.06	-0.10	0.03

Frequency response EHP50F Electric field
Measurements @ 100 V/m



Magnetic Field Frequency response for each axis at nominal magnetic flux density of 3µT.
The instrument was set as magnetic field measure with 100 Hz span up to the frequency of 100 Hz, 200 Hz span up to the frequency of 200 Hz, 500 Hz span up to the frequency of 500 Hz, 1 kHz up to 1000 Hz, 10 kHz up to 10 kHz, 100 kHz up to 100 kHz and span for frequency over 100 kHz

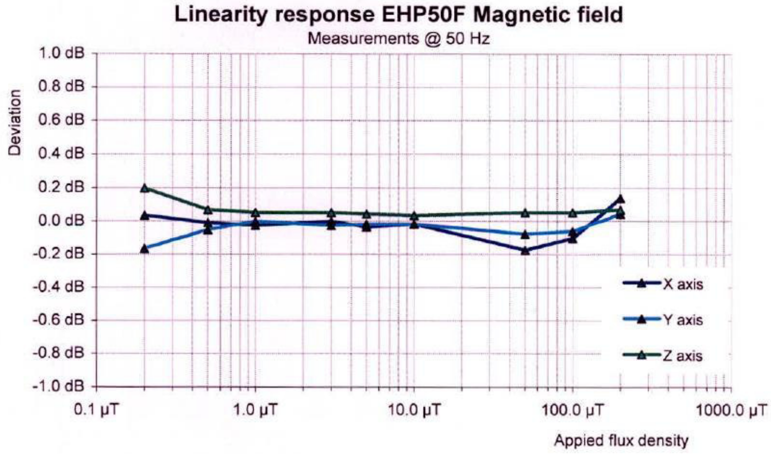
Freq. (kHz)	Deviation with 100µT range			Deviation with 10mT range		
	X axis (dB)	Y axis (dB)	Z axis (dB)	X axis (dB)	Y axis (dB)	Z axis (dB)
0.005	0.22	0.15	0.21	0.10	-0.01	0.23
0.016	0.06	0.02	0.08	-0.02	0.03	0.02
0.04	0.12	0.15	0.14	0.11	0.10	0.09
0.05	0.02	-0.02	0.18	-0.05	-0.03	0.05
0.06	0.04	-0.01	0.08	0.03	-0.09	0.05
0.10	0.02	0.11	0.01	0.01	-0.01	0.04
0.15	-0.03	0.03	-0.05	0.02	-0.02	0.03
0.20	-0.03	0.03	-0.03	0.04	-0.04	0.00
0.30	-0.10	0.03	-0.08	-0.03	-0.07	-0.02
0.50	0.04	0.06	0.08	0.03	0.00	0.10
1.0	0.02	0.01	0.03	-0.03	-0.03	-0.03
3.0	0.04	0.03	0.04	-0.12	-0.03	0.10
5.0	-0.01	-0.03	-0.01	-0.09	-0.03	0.00
10.0	-0.02	-0.03	0.00	-0.05	0.10	0.00
20.0	-0.02	-0.03	-0.07	0.03	0.09	0.00
30.0	-0.02	-0.04	-0.06	-0.02	0.07	-0.06
40.0	-0.03	-0.06	-0.03	-0.05	-0.04	-0.01
50.0	-0.01	-0.03	0.03	-0.10	0.03	-0.05
60.0	-0.02	-0.03	0.01	0.01	-0.01	0.08
70.0	-0.02	-0.01	-0.01	0.13	0.25	-0.05
80.0	-0.03	-0.02	-0.01	-0.02	0.08	-0.07
90.0	-0.03	-0.03	-0.02	-0.04	0.01	0.15
100.0	0.03	0.03	-0.03	0.15	-0.01	0.03
150.0	0.01	-0.02	-0.01	0.04	0.04	-0.17
200.0	-0.02	-0.03	-0.03	0.10	-0.33	0.18
250.0	-0.01	0.00	0.03	-0.31	0.02	0.10
300.0	-0.01	0.03	0.00	-0.15	0.10	-0.33
350.0	-0.02	-0.01	-0.02	-0.26	0.11	-0.10
400.0	-0.03	0.03	0.00	0.25	0.09	-0.02



Magnetic Field Linearity response for each axis at applied frequency of 50 Hz and magnetic flux density below
The instrument was set with 100 Hz span.

Applied flux density (µT)	Deviation		
	X axis (dB)	Y axis (dB)	Z axis (dB)
0.2	0.03	-0.17	0.20
0.5	-0.01	-0.05	0.07
1.0	-0.03	0.00	0.05
3.0	0.00	-0.03	0.05
5.0	-0.03	-0.02	0.04
10	-0.02	-0.02	0.03
50	-0.18	-0.08	0.05
100	-0.10	-0.06	0.05
200	0.14	0.04	0.07

X axis linearity 0.16 dB
Y axis linearity 0.10 dB
Z axis linearity 0.08 dB



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Determining the Recalibration Due Date
Determinazione della data di ricalibrazione

The Certificate of Calibration accompanying this product states the date that this unit was calibrated according to Narda Safety Test Solutions procedures. We have determined that the calibration of this product is not affected by storage prior to its initial receipt by the customer.
The recalibration of this unit should be based on the date when the product is put into service, plus the recommended calibration interval.

The Narda Safety Test Solutions recommended calibration interval is 24 months. To determine the date for recalibration, the customer should use the appropriate start date, and apply either the Narda Safety Test Solutions calibration interval, or an interval that satisfies their own organization's internal quality system requirements.

Il certificato di taratura che accompagna questo strumento attesta la data di taratura, quest'ultima eseguita in accordo alle procedure interne. La Narda Safety Test Solutions assicura che la taratura dello strumento non viene alterata da eventuali tempi di attesa prima del ricevimento da parte del cliente.
La ri-taratura di questo strumento dovrebbe essere effettuata adottando appropriati intervalli di taratura, a partire dalla data di messa in servizio.

La Narda Safety Test Solutions raccomanda un massimo intervallo di taratura di 24 mesi. Per determinare la data di ri-taratura, l'utente dovrebbe considerare l'intervallo raccomandato dalla Narda Safety Test Solutions o un intervallo che soddisfa i requisiti interni di qualità della propria organizzazione.

Model
Modello ____________________

Serial Number
Matricola ____________________

Put into service date
Data di messa in servizio ____________________

For additional information please contact
Per informazioni aggiuntive

Narda S.T.S. Calibration Laboratory
Via Benessea, 29/B
17035 Cisano sul Neva (SV) - Italy
Tel.: +39 0182 58641 Fax: +39 0182 586400

Apéndice D: Hoja de especificaciones técnicas NBM-550

Electric and Magnetic Field Measurements from RF to Microwave

NBM-550 Broadband Field Meter

- **Available with Isotropic Probes to cover 100 kHz to 60 GHz**
- **Large Graphical Display**
- **Intelligent Probe Interface with Automatic Probe Parameter Detection**
- **Fully Automatic Zeroing**
- **Extensive Memory for Logging of up to 5000 Results**
- **GPS Interface and Mountable Receiver for Positioning Data Documentation (Optional)**
- **Voice Recorder for Adding Comments (Optional)**

Description

The NBM-500 Series is the most accurate non-ionizing radiation survey system available. It provides the broadest frequency coverage of electric and magnetic fields. Both flat response probes and probes shaped to international standards are available. All NBM probes have a non-volatile memory containing device parameters and calibration data. Probes are calibrated independently of the meter. Any NBM probe can be used with any NBM-500 Series meter and still maintain total calibration.

Applications

Precision measurement of electric or magnetic field strength for personal safety at work where high radiation levels are present, such as:

- General RF Safety program measurements
- Service work on transmitting and radar equipment
- Service work on mobile antennas, broadcasting and satellite communication systems
- Working with heating and packaging machines in the food industry
- Working with heating and hardening machines in the automotive industry
- Operating diathermy equipment and other medical instruments producing short-wave radiation
- Drying equipment in the tanning and timber industries

Electric and Magnetic Field Measurement

NBM-550 Broadband Field Meter

Rugged and lightweight housing, designed for easy one-hand operation

Features

DISPLAY
- Backlit Monochrome LCD; readable even in bright daylight
- Graphical User Interface (GUI) with selectable languages

OPERATION
- Simple-to-Use 9 button keypad
- Hold button soft key for "freezing" measurement display during readings
- User defined setups can be saved for repetitive survey needs
- Keypad can be locked to guard against inadvertent inputs
- User selectable "auto-off" feature to save battery life

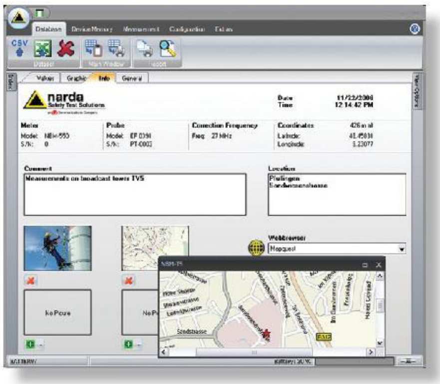
READINGS DISPLAYED
- 5 Types of results can be displayed - actual, minimum, maximum, average and maximum average
- History Mode – history memory operates continuously in the background, allowing you to display past readings at any time, up to 8 hours
- Selectable Units – V/m, A/m, W/m^2, mW/cm^2 and "% of Standard" when using shaped frequency response probes
- Stored standards and guidances in the NBM's memory allow you to simultaneously display readings as a "% of Standard" if frequency is known
- Data memory for up to 5000 measurements

AVERAGING FUNCTIONS
- Time Averaging – 4 seconds to 30 minutes, in 2-second intervals
- Spatial Averaging – discrete or continuous

AUDIBLE ALARM
- Variable alarm threshold setting
- Audible indication of increasing or decreasing field strength

PROBE INTERFACE
- Automatic detection of probe type and calibration information
- Fully automatic and variable zero adjustment interval times
- Additional optical input for separating probe from meter

REMOTE CONTROL
- PC connection via USB or Optical interface
- Trigger input for externally initiating readings to be taken
- NBM-TS software enables remote controlled measurements
- Screenshots can be downloaded to PC



NBM-TS Software (supplied with NBM-550)

The supplied NBM-TS software provides for convenient data management, documentation of results and future evaluation. It also provides you the capability to remotely control the NBM and perform firmware upgrades. This innovative software package also allows you to link the optional GPS data with actual pictures from mapping programs like Google Earth™, making field survey data take on more relevance with the reader. And, to ensure it will be viable for years to come, this software was designed with Microsoft's Vista™ operating system in mind.

NBM Option Set

Consider the Option Set for the NBM-550 and how it can simplify your survey reports – a major advantage. This Option Set adds a GPS receiver and conditional logging. It also allows you to add voice storage to stored readings via our built-in microphone. By adding the power and versatility of audible comments to stored readings, you will not have to remember the particulars of when and where readings were taken – imagine that!

THE NBM-550 OPTION SET INCLUDES:
The Option Set is field (or factory) installable, so it can be added any time you choose, without having to return it to the factory.

***NOTE:** Narda strongly recommends that an optional check source be used to verify operation of the NBM Series. Any device capable of generating an upscale indication at microwave frequencies is acceptable, as well as Narda P/N 8699.*

NBM-550 Broadband Field Meter

Specifications

NBM-550	
DISPLAY	
Display Type	Transflective LCD, monochrome
Display Size	10 cm (4 inch), resolution 240 x 320 dots
Backlight	White LEDs, selectable illumination time (OFF, 5s, 10s, 30s, 60s, PERMANENT)
Refresh Rate	200 ms for bar graph and graphics, 400 ms for numerical results
MEASUREMENT FUNCTIONS	
Result Units	mW/cm^2, W/m^2, V/m, A/m, % of Standard
Display Range, Fixed Triads	0.0001 to 9999 for all units (4 digits)
Display Range, Variable Triads	0.01 V/m to 100 kV/m 0.027 mA/m to 265.3 A/m 0.265 µW/m^2 to 26.53 MW/m^2 0.027 nW/cm^2 to 2.653 kW/cm^2 0.0001% to 9999%
Result Types (Isotropic, RSS)	Actual (ACT), Maximum (MAX), Minimum(MIN), Average (AVG), Maximum Average (MAX AVG)
Result Types (X-Y-Z mode)	Actual X, Actual Y, Actual Z (requires a probe with separate axes)
Averaging Time	Selectable, 4 seconds to 30 minutes (2 second steps)
Spatial Averaging	Discrete or continuously
Multi-position Spatial Averaging	Averaging of up to 24 spatially averaged results, each position and total will be stored
History View	Graphical display of actual results versus time (span of 2 minutes to 8 hours)
Frequency Correction	1 kHz to 100 GHz or OFF (direct frequency entry, interpolation between calibration points)
Hot Spot Search	Audible indicator for increasing and decreasing field strength (result type Act or Max)
Alarm Function	2 kHz audible signal (4 Hz repetition), adjustable threshold
Timer Logging	Start time pre-selection: up to 24 hours or immediately Logging duration: up to 100 hours Logging interval: 1 second to 6 minutes (in 11 steps)
RESULTS MEMORY	
Physical Memory	12 MB non-volatile flash memory for measurement results and voice comments
Storing Capacity	Up to 5000 results (including test parameters, time stamp and GPS data when available)
INTERFACES	
Remote Control	Via USB or optical RS-232 interface (selectable)
USB	Serial, full duplex, 460 kBaud (virtual COM port), multi-pin connector
Optical Interface	Serial, full duplex, 115 kBaud, no parity, 1 start and 1 stop bit
Earphone	3.5 mm TRS, > 16 ohms (mono), for voice recorder option only
External Trigger (to store results)	Uses the multi-pin connector. Interface cable with BNC connector available as an option, triggers when contacts shorted.
External GPS Receiver	Uses the multi-pin connector. GPS receiver with interface cable is available as an option
Probe Interface	Plug-and-play auto detection, compatible with all NBM series probes

NBM-550 Broadband Field Meter

Ordering Information

NBM-550	Ordering Part No.
NBM-550 Narda Broadband Field Meter System Includes: NBM-550 Basic Unit (2401/01B) Transit Case, holds field meter and up to 5 probes (2400/90.06) Power Supply / Charger 100 VAC to 240 VAC Input, 9 VDC Output (2259/92.06) NBM-TS Software and PC Transfer (2400.93.01) USB Interface cable for NBM, 2 m (2400/90.05) Bench-top Tripod, 0.16 m, non-conductive 2244/90.32) Shoulder Strap, 1 m (2244/90.49) Operating Manual Certificate of Calibration ***Probes are NOT included***	**2400/101B**
Option Set for NBM-550 (GPS Interface and Receiver, Voice Recorder, Conditional Logging)	**2401/40/USA**
PROBES	
Probe EF 0391, E-Field, 100 kHz – 3 GHz, Isotropic	**2402/01B**
Probe EF 0392, E-Field, 100 kHz – 3 GHz, Isotropic	**2402/12B**
Probe EF 0691, E-Field, 100 kHz – 6 GHz, Isotropic	**2402/14B**
Probe EF 1891, E-Field, 3 MHz – 18 GHz, Isotropic	**2402/02B**
Probe EF 5091, E-Field, Thermocouple, 300 MHz – 50 GHz, Isotropic	**2402/03B**
Probe EF 5092, E-Field, Thermocouple, 300 MHz – 50 GHz, Isotropic	**2402/11B**
Probe EF 6091, E-Field, 100 MHz – 60 GHz, Isotropic	**2402/04B**
Probe HF 3061, H-Field, 300 kHz - 30 MHz, Isotropic	**2402/05B**
Probe HF 0191, H-Field, 27 MHz – 1 GHz, Isotropic	**2402/06B**
Probe EA 5091, Shaped E-Field, FCC, 300 kHz - 50 GHz, Isotropic	**2402/07B**
Probe EB 5091, Shaped E-Field, IEEE, 3 MHz - 50 GHz, Isotropic	**2402/08B**
Probe EC 5091, Shaped E-Field, SC6, 300 kHz - 50 GHz, Isotropic	**2402/09B**
Probe ED 5091, Shaped E-Field, ICNIRP, 300 kHz - 50 GHz, Isotropic	**2402/10B**
ACCESSORIES	
Test-Generator 27 MHz, Hand-Held	**2244/90.38**
Tripod, Non-Conductive, 1.65 m with Carrying Bag	**2244/90.31**
Tripod Extension, 0.50 m, Non-Conductive (for 2244/90.31)	**2244/90.45**
Handle, Non-Conductive Extension 0.42m	**2250/92.02**
Cable, Coaxial Multi-pin / BNC for NBM-550 External Trigger, 2 m	**2400/90.04**
Cable, Fiber Optic Duplex (1000 µm) RP-02, 2 m	**2260/91.02**
Cable, Fiber Optic Duplex (1000 µm) RP-02, 20 m	**2260/91.03**
Cable, Fiber Optic Duplex FSMA / RP-02, 0.3 m	**2260/91.01**
O/E Converter RS-232C (RP-02/DB-9)	**2260/90.06**
O/E Converter USB (RP-02/USB)	**2260/90.07**
Cable, Adapter, USB 2.0 - RS-232, 0.8 m	**2260/90.53**

Apéndice E: Matriz de Consistencia

MATRIZ DE CONSISTENCIA

Problemas	Objetivos	Metodología
Problema Principal ¿En qué medida el diseño e implementación del prototipo aporta tecnológicamente al Perú para las futuras mediciones que podrían realizar las instituciones estatales y privadas? **Problema Específicos** • ¿En qué medida el diseño e implementación favorece a la población? • ¿Qué dificultad se obtuvo al diseñar las sonda de campo magnético y eléctrico? • ¿Qué tan exactos fueron las mediciones realizas por el prototipo diseño e implementado a comparación?	**Objetivo General** Diseñar e implementar un prototipo medidor de campo eléctrico y magnético de baja frecuencia. **Objetivos Específicos** • Diseñar e implementar las sondas de los campos magnéticos y eléctricos. • Diseñar e implementar la parte inteligente de ambos módulos para el procesamiento, almacenamiento de datos y comunicación entre ellas mediante fibra óptica. • Realizar las pruebas de operación del equipo de exposición y contrastar con el equipo NARDA EFA 300. • Accesibilidad de un equipo de bajo costo con seguridad en la medición los campos electromagnéticos de baja frecuencia.	**Tipo de investigación** El presente trabajo es una de enfoque cuantitativo. **Diseño de la investigación** El presente trabajo responde al de una investigación no experimental del tipo transversal. **Técnicas** Las técnicas que se ha empleado en la investigación son las mediciones de campo de la intensidad de campo eléctrico, basado en un protocolo de medición según normativas **Instrumentos** Los principales instrumentos que se usaron fue el equipo de medición EFA 300 y NBM 550.

Apéndice F: Tabla de niveles medidos de campos electromagnéticos en equipos eléctricos domésticos

Intensidades de campo eléctrico típicas medidas cerca de electrodomésticos (a una distancia de 30 cm) Fuente: Oficina federal alemana de seguridad radiológica (Bundesamt für Strahlenschutz, BfS), 1999.

Electrodoméstico	Intensidad del campo eléctrico (V/m)
Receptor estereofónico	180
Hierro	120
Frigorífico	120
Batidora	100
Tostadora	80
Secador de pelo	80
Televisor de color	60
Cafetera eléctrica	60
Aspiradora	50
Horno eléctrico	8
Bombilla	5
Valor límite recomendado	5000

Nota: Recopilado *(OMS, 2018)*

Intensidades del campo magnético típicas de algunos electrodomésticos a diversas distancias

Aparato eléctrico	A una distancia de 3 cm (μT)	A una distancia de 30 cm (μT)	A una distancia de 1 m (μT)
Secador de pelo	6 – 2000	0,01 – 7	0,01 – 0,03
Máquina de afeitar eléctrica	15 – 1500	0,08 – 9	0,01 – 0,03
Aspiradora	200 – 800	2 – 20	0,13 – 2
Luz fluorescente	40 – 400	0,5 – 2	0,02 – 0,25
Horno de microondas	73 – 200	4 – 8	0,25 – 0,6
Radio portátil	16 – 56	1	< 0,01
Horno eléctrico	1 – 50	0,15 – 0,5	0,01 – 0,04
Lavadora	0,8 – 50	0,15 – 3	0,01 – 0,15
Hierro	8 – 30	0,12 – 0,3	0,01 – 0,03
>Lavavajillas	3,5 – 20	0,6 – 3	0,07 – 0,3
Computadora	0,5 – 30	< 0,01	
Frigorífico	0,5 – 1,7	0,01 – 0,25	<0,01
Televisor de color	**2,5 - 50**	**0,04 – 2**	**0,01 – 0,15**

Fuente: Oficina federal alemana de seguridad radiológica (Bundesamt für Strahlenschutz, BfS), 1999. (La distancia de operación normal se indica en negrita.)